Hidden hazards and dangers associated with the use of HME/®lters in breathing circuits. Their effect on toxic metabolite production, pulse oximetry and airway resistance

E. G. Lawes

Shackleton Department of Anaesthesia, Southampton University Teaching Hospitals, Tremona Road, SO16 6YD, UK
E-mail: riclawes@ntlworld.com

Br J Anaesth 2003; 91: 249–64

Keywords: complications; equipment, filters

Filter technology

Current airway dust ®lter technology emanates from the USA mining industry during the 1930s. It was further developed and improved by the USA military during World War II to prevent workers from inhaling very fine radioactive particles in the nuclear industry. These later filters we now recognize as high ef®ciency particulate air ®lters (HEPA).

The ef®ciency of ®lters varies according to the number and size of particles they capture. Filters may be classi®ed commonly as 95, 99.95, and 99.97% ef®cient (95, 99 and 100, respectively). The higher the ef®ciency the higher the classi®cation number used. The ef®ciency of ®lters may also be affected by volatile chemicals which may be inhaled with the particles. Industrial ®lters which are categorized by the above system may also have a pre®x of N, R, or P; N for Not resistant to oil, R for Resistant to oil, and P for oil Proof; thus, a ®lter would be classi®ed as for example a P100. Requirements for military and environmental biohazard ®lters are based on these classi®cations and surprisingly may only achieve 95% ef®ciency.

A generally perceived increased threat from biological hazards that may be inhaled, including bioterrorism threats, especially in hospital environments, has increased interest in respiratory ®lters.94 Protecting personnel from inhaled biological hazards requires a ®lter ef®ciency of several orders of magnitude greater than the industrial dust ®lters used in respirators alluded to above. As few as 10 inhaled smallpox viruses may be sufficient to infect patients with the disease.94 This has resulted in the sub-classi®cation of HEPA ®lters into true HEPA ®lters and HEPA type ®lters. A further sub group has also developed. ULPA ®lters (Ultra Low Penetration Air) and ‘absolute’ ®lters are designed for industrial applications such as microelectronic clean rooms, but have too high a resistance for medical breathing apparatus.

All HEPA ®lters are manufactured from glass fibre materials supported on a rigid frame. In order to reduce resistance to air ¯ow and increase ef®ciency, the surface area is increased by pleating. Filtration is achieved for larger particles (>0.3 μ) by inertial impaction and interception; smaller particles are captured by Brownian diffusion. The size of particles used to test ®lters is measured in microns. Microns are units used for particles that can be seen with a light microscope. A micron is a thousandth of a millimeter, which is in turn a thousandth of a meter (1 μ=1000 nm or 0.001 mm). The variation in ®ltration ef®ciency is tested by the British BS3928 Sodium Flame method and the USA Hot DOP method. The most dif®cult particle size to capture by ®ltration is a particle of 0.3 μ as at this size the effects of inertial impaction, interception and Brownian motion are least effective. Particles of 0.3 μ are also most likely to be deposited in the lungs if inhaled. The di-octyl-phthalate (DOP) test, used for testing the ef®ciency of ®lters, takes advantage of the properties of DOP. In particulate form, DOP has a constant mean diameter of 0.3 μ. By passing DOP through the ®lter, the capturing ef®ciency can be classi®ed. Bacterial size generally equates to 0.3 μ; virus sizes are considerably smaller (Table 1). Wilkes has recently used the sodium chloride test for measuring ®lter ef®ciency on 33 breathing system ®lters (nine pleated hydrophobic and 24 electrostatic filters). A particle of 0.3 μ is also most likely to be deposited in the lungs if inhaled. The di-octyl-phthalate (DOP) test, used for testing the ef®ciency of ®lters, takes advantage of the properties of DOP. In particulate form, DOP has a constant mean diameter of 0.3 μ. By passing DOP through the ®lter, the capturing ef®ciency can be classi®ed. Bacterial size generally equates to 0.3 μ; virus sizes are considerably smaller (Table 1). Wilkes has recently used the sodium chloride test for measuring ®lter ef®ciency on 33 breathing system ®lters (nine pleated hydrophobic and 24 electrostatic filters). The particles in this test are considerably smaller than those of the DOP test and have a size distribution with a median diameter of 0.07 μ and a geometric standard deviation not exceeding 1.83.110
A filtration efficiency of 99.999% indicates that only one particle of 100,000 challenging the filter has the potential for penetration beyond the filter. Even if a filter package states that it is 99.97% efficient it is not necessarily a true HEPA filter unless this efficiency was achieved using particles of 0.3 μ. HEPA type filters are made of the same materials as true HEPA filters but they may achieve as little as 25% efficiency. A third type of filter known as an electrostatic filter was, until recently, unable to achieve this level of filtration, but some are now capable of achieving efficiencies of 99.999%.

Aside from presenting a barrier to inhalation of organisms and latex particles, filters may be modified to perform additional functions. These are to conserve patient’s body heat and to ensure an adequate moisture content of inhaled anaesthetic and respiratory gases in order to protect airways from drying out. With these modifications, filters function as heat and moisture exchanger filters (HMEF). The filters in industrial HEPA respirators are usually colour coded, for example, magenta (reddish-purple), in order to quickly identify the purpose for which the filter is designed, that is to protect against dust, volatile solvents, spray paints, etc. The different functions of medical filters are also identified by at least one manufacturer (Intersurgical\(^\text{59}\)) by colour coding their products in a way similar to industrial filters thus enabling the most appropriate use of the device (Table 2).

The manufactures of all heat and moisture exchangers (HME) are expected to adhere to voluntary standard ISO 9360 ‘Anaesthetic and Respiratory Equipment—Heat and Moisture Exchangers for Use in Humidifying Respired Gases in Humans’.\(^\text{59}\) This standard provides advice concerning the construction of the filter housing, connections suitable for anaesthetic circuits, labelling, and packaging. The most important section of this standard is Section 6, ‘Test Methods’. This section ensures all devices are tested by the same methods, under the same conditions of tidal volume, breathing frequency, and duration of test (24 h), thus facilitating objective appraisal of similar devices. The efficiency of a HME is tested by adding a precise level of moisture at a precise temperature setting (34°C and 37.6 mg H\(_2\)O litre\(^{-1}\) of inspired air) and is maintained during the 24 h test period. A detailed review of the structure of HMEs in relation to their function is given by Wilkes.\(^\text{109}\)

**Efficacy of HME/filters is not proven**

The idea that the ‘wrong filter’ can lead to disaster will come as no surprise to observers of modern history or investigators of civil aviation disasters. Spectacular examples are the abortive Iranian hostage rescue in the Middle East in the early 1980s, during which the USA marines’ helicopters were grounded by sand in their engines, and the failure of Britain’s main battle tank in the Gulf and more recently in Oman. All were because of the inappropriate use of the engine air intake filters that were unsuited to the prevailing environment and, in the latter cases, as the result of cost cutting. Similar problems have repeated themselves in the current Afghan crisis.

Recently, anaesthetic departments have been asking whether they should carry the cost of single use, disposable anaesthetic circuits, discarded between cases, in order to avoid cross contamination between patients. Alternatively, should we rely on the properties of single use disposable filters, whilst retaining the circuits? Disposing of filters is cheaper than disposing of circuits, but which filters are the right ones and which are the wrong ones? Are we changing one set of problems for another? The debate is neither new nor resolved but it would be advisable to examine these options closely.
Christopher and colleagues, and Wille highlight the risks of cross infection that are presumed to exist following long-term mechanical ventilation and short-term anaesthesia. Numerous articles and reviews attest to the advantages of breathing system filters, circuit filters, HME, and HMEF, with or without bactericidal properties, introduced to avoid the risk of cross contamination. The properties and performance characteristics of these devices have been investigated by Hedley and Allt-Graham in the laboratory under simulated clinical conditions. As a result of this, and similar investigations that demonstrate the beneficial properties of filters in the laboratory, there is a danger of implementing poorly thought out guidelines requiring the use of filters in clinical settings without considering all of the consequences. Filters are being used in the interests of economy and legislation, aside from clinical indications, and without regard to the properties of these devices. The potential detrimental consequences of making such a simple change to clinical practice as to include one of these devices in an anaesthetic circuit are rarely highlighted.

**Filters in the ITU**

There is some overlap between the requirements for heat and moisture conservation and biological filtration for long-term mechanical ventilation in intensive care, and short-term ventilation using circle absorbers in operating theatres, but there are also marked differences. It is instructive to consider the evolution of filters introduced in intensive care units (ITU) following laboratory investigations. Their introduction was not without mishap.

**Airways resistance**

Numerous studies highlight the increased resistance to breathing associated with filters. HME with bacterial filtering capabilities were investigated in an intensive care environment by Cohen and colleagues. They concluded that not only did this early model of a HME not provide sufficient airway humidification but also their use was associated with an increase in tracheal tube occlusion, atelectasis, and an increased incidence of pneumonia. Not all technical problems had been resolved 6 yr later and it was noted that increased resistance could interfere with patient monitoring. Manthous and Schmidt were one of the first to criticize the indiscriminate use of humidifiers in ITU. They concluded that the humidifier added a significant resistance to the ventilator circuit that may lead to incorrect assessment of respiratory system mechanics; to inappropriate therapy (e.g. bronchodilators); or to difficulty in weaning from mechanical ventilation. Le Bourdelles and colleagues also reported difficulties weaning patients from mechanical ventilation when using HMEs in an ITU. These authors’ findings and their concerns were similar to those of others dealing with weaning from mechanical ventilators. Problems primarily related to airways resistance persisted. Pelosi and colleagues warned that as HMEs substantially increase minute ventilation, ventilatory drive, and work of breathing, these devices should be used carefully in patients with acute respiratory failure during pressure-support ventilation. However, they pointed out that an increase in pressure-support ventilation (5–10 cm H₂O) might compensate for the increased work of breathing. Iotti and colleagues concluded that HMEs cause unfavourable mechanical effects by increasing inspiratory resistance, ventilation requirements, and dynamic intrinsic PEEP. They warn clinicians to consider these effects when setting mechanical ventilation and when assessing patients’ ability to breathe spontaneously.

In contrast, Subayi and colleagues reviewed the literature following a Medline search. They concluded that despite reservations such as those above and others like them, that the evidence in the literature not only supported using an HMEF but that they were highly recommended in intensive care and are essential during anaesthesia.

**Filters in ITU breathing circuits**

There is no doubt that circuit colonization occurs in unfiltered long-term ventilated patients in ITU. No one would risk cross contamination between patients by reusing such circuits on consecutive patients. The significance of circuit colonization in a patient’s own breathing system is, however, largely unknown. Circuit colonization is not necessarily associated with an increased incidence of pneumonia. Dreyfuss and colleagues were able to demonstrate that ventilator tubing contamination was considerably reduced with the use of a heat and moisture exchanger. In contrast, bacterial colonization of the pharynx and trachea was identical to that found in the control group without a HME. The authors suggest that provided the usual hygiene and maintenance precautions are applied, circuit colonization plays little or no role in the occurrence of ventilator-associated pneumonia.

The way in which HMEs are used in ITU is changing subtly with doubts being cast on the necessity to change filters frequently. The need to replace more recent designs of HMEs on a daily basis during mechanical ventilation has been investigated by Davis and colleagues. The authors investigated recently introduced hydrophobic or hydroscopic HMEs and found that using the device for 3 days between changes does not diminish their efficiency, increase resistance, or alter bacterial colonization. They noted that with this regime there was also no increase in the frequency of nosocomial pneumonia. They concluded that it is safe and cost effective to use HMEs for >24 h, and certainly up to 72 h. Ricard and colleagues extended the change interval and concluded that mechanical ventilation can be safely conducted in non-COPD patients using an HME changed only once a week, and that this is safe, efficient, and cost-effective. This interval between the need to change used filters for fresh ones has been confirmed by Han and
colleagues who investigated the possibility of retaining the HME for 7 days and also found the devices to be equally effective after this interval. Littlewood and Durbin take the argument a stage further and contend that there is little evidence to support using HME at all, and that there is substantial evidence to support the changing of ventilator circuits no more frequently than once every 7 days. However, until the change interval has been investigated further, it is important that anaesthetists understand the significance and responsibilities of using devices outside the limits of their product licences.

Filters in anaesthetic circuits

Atkinson and colleagues found that the terms for filters, HMEFs and HMEs are commonly used interchangeably without reference to their efficiency in respect of either bacteriological function or heat and moisture conservation. A consequence of the interchangeable use of the terms for filters and HMEs is that anaesthetist’s attitudes towards filters are varied and inconsistent as to both their cost effectiveness and their ability to prevent cross contamination between patients. Wilkes and colleagues remind us that the use of HMEs may be inappropriate for some patient groups and the significance of their placement in anaesthetic circuits is poorly understood. This lack of differentiation between different devices may have an unexpected impact on the more complex circumstances of an anaesthetic circuit compared with an intensive care ventilator, especially in conjunction with circle absorbers. Elucidating the problems associated with filters in these circumstances depends more on laboratory investigations, case reports and correspondence rather than prospective clinical trials.

Current product licences require that single use anaesthetic circuits be used once and replaced between patients to eliminate the potential, but unclear risk, of infection between consecutive patients. The financial implications are enormous. The strategy of incorporating a fresh sterile filter in the circuit and changing this, whilst retaining the circuit between cases, has been suggested by Berry and Nolte as a cheaper alternative to discarding the circuit. The consequence of this recommendation is that filters are now commonly placed on every anaesthetic circuit without reference to pertinent arguments regarding the wisdom of such action.

Laboratory studies point to the potential of bacterial cross contamination between patients using unprotected anaesthetic circuits. The magnitude of potential cross contamination between patients during routine and short procedures in fit, well patients, whose immune system is not compromised is, however, largely unknown. Contamination of circuits is not the same as contamination occurring between two consecutive patients on an operating list. The Association of Anaesthetists (GBI) have published recommendations regarding the use of bacteriological filters and their use in preventing cross infection. Wilkes and Stevens provide additional guidance; however, Stevens warns of inconsistencies in performance between filter manufacturers, the consequence of which is that not all filters are equally effective. This difference in filter efficiency between manufacturers may explain the contradictory nature of articles investigating the beneficial effects on contamination of filtration of anaesthetic circuits.

The original report by Chant and colleagues that reawakened us to the possible role that liquid from an unfiltered breathing circuit played in transmission of Hepatitis C virus came from Australia. In this report, consecutive use of the anaesthetic circuit was thought to be the link between the patients. Hepatitis transmission through a reusable part of an anaesthetic system was thought to be a possible mode of transmission in a further incident reported by Heinsen and colleagues. Although the virus involved was clearly genetically identical in the two patients, this specific route of transmission could not be established conclusively.

If cross contamination with hepatitis did occur in the manner suggested, what would have been the effect of using a filter? If a filter is used, which one should it be? It is by no means clear that the presence of a filter would have prevented such an unusual means of transmission of Hepatitis C, or even whether we can trust all filters to protect our patients against this or any other organism if filters are used. The barrier to organism transmission varies in effectiveness between different filter manufacturers' products. Lloyd and colleagues investigated this problem by examining the transfer of viruses through filters and concluded that not all filters are equally suited to preventing the passage of viruses.

Leijten and colleagues contested the old idea that halothane and soda lime had bactericidal properties and demonstrated, in a laboratory experiment, that without a HMEF the whole interior of the anaesthetic circuits becomes contaminated with bacteria thus supporting the use of filters. The protection of the anaesthetic circuits by a filter is also tentatively supported by Vezina and colleagues. These authors demonstrated that using a sterile DAR Barrierbac S breathing filter for every patient was highly effective at preventing, but not eliminating contamination of the anaesthesia breathing circuit. They calculated that the use of this filter would result in a cross contamination rate of the breathing circuit less than once in every 250 cases.

du Moulin and Sauberman investigated this problem many years ago and concluded that anaesthetic machines were unlikely sources of contamination and that basic hygienic management of anaesthesia machines ensured patient safety. Garibaldi and colleagues, in a blinded prospective study of 520 patients undergoing anaesthesia, investigated the use of filters during anaesthesia and concluded that circuit filters played no part in the incidence of postoperative chest infection. Hogarth goes one step further, and points out that although filters can be shown to
decrease circuit colonization in laboratory studies, they have not been proven to decrease ventilator-pneumonia infection rates.\textsuperscript{57} He contends that the use of filters is based less on science than on defensive medical practice. In a clinical study, Rathgeber and colleagues found that only 13% of anaesthetic circuits become contaminated with bacteria if used without filters.\textsuperscript{87} In this study the author concedes that circuit contamination occurs, but despite this he was unable to confirm either an increase or a decrease in the incidence of patient infections. More recently, Body and Philip came to the conclusion that the use of filters may not influence the incidence of cross contamination and expressed their reservations in using circuit filters.\textsuperscript{21} Following their investigations of water trap contamination on their anaesthetic machines despite using filters, they have elected to use disposable circle anaesthesia circuits and a regular (daily) cleaning programme without the use of filters.

The inconsistency between the results of these studies lies in the failure of manufacturers, until recently, to state the efficiency of their filters. Many manufacturers claim 99.95\% efficiency for their filters, whilst the early recommendations from Lumley and colleagues were that filters should be at least 99.9977\% efficient (i.e. only 23 per $1 \times 10^6$ organisms to pass through). 99.9999\% efficient is 10 times more efficient than 99.9999\%, 100 times more efficient than 99.9999\% and 1000 times more efficient than 99.9999\%.\textsuperscript{69}

Even if filter efficiency is published by a manufacturer, a confounding factor is the microenvironment of the circuit and the filter that develops in a clinical setting. Not all filters perform in the same manner when presented with either wet or dry challenges. Hedley and Allt-Graham published two papers revealing their findings that some filters are better at filtering dry particles, and some at wet particles or fluid.\textsuperscript{51 52} Mebius investigated, in the laboratory, the physical characteristics, humidification efficiency, filtration capability, and resistance to flow of six commercially available HMEs with built-in bacterial filtration.\textsuperscript{75} He also reported small but significant differences between average filtration capability and humidification efficiency between different manufacturers. The clinical significance of this range of filter efficiency is very important when making the judgement to either use or omit the filter, and which other circuit components should also be discarded between patients, even if a filter has been used. Differences in efficiency are not easily available to users; information on product inserts is lacking.

Wilkes and colleagues investigated the ability of a mixed selection of electrostatic and pleated hydrophobic membrane filters to prevent the passage of fluid across filter membranes.\textsuperscript{107 113} Their model was designed to accurately reflect the behaviour of contaminated fluid present in used anaesthetic circuits. Again, inconsistencies in performance were demonstrated, and in some instances the filters failed to form an effective barrier. Hydrophobic filters tended to out-perform electrostatic filters, but were associated with increases in airway resistance. The variation in performance again raises the question, which filter in which circumstances? They remind us that filters are contraindicated in the presence of copious secretions (either sputum or pulmonary oedema).

In an attempt to untangle the results, Wilkes and colleagues investigated the bacterial and viral filtration qualities of filters using the test methods specified in the draft European standards BS EN 13328-1.\textsuperscript{106} Whilst variations in performance were found, the essential value of this paper was to enable comparisons between filters to be made as a result of a common testing method. More recently, the performance characteristics of filters were found by Wilkes to vary depending not only on their mode of construction (pleated hydrophobic or electrostatic), but also the orientation of the filter layer, adding a further uncertainty to their universal efficacy.\textsuperscript{110}

Some authors contend that even if a filter is used, it is not sufficient just to change filters between patients. Neft and colleagues undertook a study on anaesthetized patients in the operating room, comparing bacteriostatic vs non-bacteriostatic HMEs (BHMEs/NHMEs) to assess their role in preventing bacterial transmission to the anaesthesia breathing circuit. Neither HME prevented contamination of the machine side of the circuit.\textsuperscript{81} Their results support discarding breathing circuits even if a filter is used. The idea of throwing away a filter and retaining the circuit between each patient is attractive on economic grounds, although Hess points out that this raises several ethical issues, especially when some authors state that the filters they investigated failed to keep the circuits clean, as alluded to above.\textsuperscript{55} Snowdon points out in his editorial that few anaesthetists would suggest or know which medical breathing circuit filters are sufficiently ineffective to risk cross contamination with hepatitis viruses or tuberculosis.\textsuperscript{95} Even with a filter, most anaesthetists would prefer to discard both filter and circuit in the above circumstances as the efficiency of any given filter is hard to identify at present.

Some attempt at standardization of biohazard filter efficiency has been made in the USA. Nardell looked at biohazard filters for protecting workers against airborne pathogenic organisms to which health workers are frequently exposed.\textsuperscript{80} Two organisms feature in this standardization, tuberculosis and hantavirus; infection with the latter has a mortality rate of approximately 70\%. Existing recommendations for protecting workers from biological hazards require the use of half-mask or full face-piece air-purifying respirators with particulate filter efficiencies ranging surprisingly from N95 (95\% efficient for hazards such as pulmonary tuberculosis) to P100 (99.97\% efficient, referred to as 100\% for hazards such as hantavirus) as a minimum level of protection.

Many commercial circuit filters now exceed this minimum level of protection. In the UK, safety documents relating to exposure to biohazards are published by the
Health and Safety Executive and COSHH, both accessible online at www.ukonline.gov.uk. HEPA filter terminology is still in use in the UK but has largely been discarded in the USA. P100 filters equate to HEPA filters, but this does not distinguish true HEPA filters from HEPA-like filters. Clearly terminology remains confusing.

In response to this dilemma of how effective filters are, and in order to contain the costs of discarding circuits, initially one, then other manufacturers, developed highly efficient products with the objective of enabling circuits to be retained whilst discarding filters between cases. They have obtained product licences indemnifying users to use a circuit for intervals up to a week, provided they use a fresh filter (that they also manufacture) for every case. This product licence may not reflect the efficiency of this option so much as it reflects the lack of evidence that there is a real problem in routine anaesthesia, as has been noted above. The product licence has various stipulations. Publications of this nature are of course helpful in demonstrating manufacturers’ willingness to respond to clinical problems. The data are, however, inadmissible for evidence-based practice without independent verification, as there is a clear conflict of interest. Independent clinical verification of the efficacy of this strategy is now beginning to emerge with demonstrable cost savings. Daggan and colleagues demonstrated, in a clinical study, that it is possible to reuse an anaesthetic breathing circuit at least twice if the circuit is filtered by one of these highly efficient filters, but suggest that further studies are needed.35

Adopting a policy based on these product licences may not be as expedient as it first appears. From the viewpoint of a company lawyer, without recording equipment batch numbers, implementing and auditing rigid hygiene training protocols and monitoring all patients on an operating list for pathological organisms both before and after anaesthesia, the indemnity provided by this product licence is moot. Proving a failure of filtration will be almost impossible. The laboratory and labour costs of implementing these changes would seem to be in excess of potential savings.

Numerous publications attest to the beneficial effect of HMEs, HMEFs and filters variously on the economics of disposable devices, heat conservation, preservation of tracheobronchial mucosal integrity, and the potential for reduction in cross contamination. Barbara and colleagues have even shown them to be effective in the filtration of latex particles.7 Laboratory studies, however, as noted previously, show circuit colonization both with and without filters. Furthermore, patient studies fail to demonstrate differences in the incidence of infection in these two circumstances. Despite all this contradictory evidence, the temptation is to assume that placing filters on every anaesthetic circuit is a prudent intervention, devoid of adverse consequences. This represents defensive medicine and has little bearing on the known facts and, as so often happens because of hidden hazards, this policy may actually do more harm than it seeks to avoid. No general article has sought to warn of some of the numerous disadvantages incurred by introducing such devices into anaesthetic circuits or of the potential consequences of mixing circle absorbers and HMEs.

Disadvantages of the use of HME filters

Filter obstruction

The routine use of filters is not without hazard. Filters are designed to obstruct the passage of one component or other of a gas or liquid presented to them. That this ability to obstruct should cross the cusp of selective obstruction to total obstruction is, in certain circumstances, inevitable. Filters can obstruct completely, partially, suddenly or over a longer time span. Detection and interpretation of the changes to resistance that occur is difficult. Extreme caution should be exercised when the filter is out of sight, difficult to access and concealed by sterile drapes. Following a near fatal accident with an obstructed filter, McEwan and colleagues recommended that the routine use of filters be discouraged.72 His recommendations some of which are listed in Table 3 are as valid now as when they were made in 1993.

These recommendations cover most but not all of the problems associated with filter use. Other authors have reported similar near fatal complications that have resulted as a consequence of partial or complete airways obstruction during anaesthesia when using a filter.10 24 27 50 84 85

Similar problems of filter obstruction have been reported by Barnes and Normoyle (Table 4) who, when attempting to ensure adequate airway humidification of an infant’s airway found that the filter obstructed.9 Active humidification is a contraindication to the use of the HME. Stacey and colleagues and others had similar experiences of obstruction following the use of nebulized medications.97 Walton and colleagues reported two cases of filter obstruction during the management of bronchospasm with the nebulized beta-2-

| Filters, if used, should be placed in the inspiratory limb or at the tracheal tube connector |
| Routine use of filters should be discouraged |
| Anaesthesia machine pressure alarms should be located on the patient side of the expiratory valve |
| Each anaesthesia machine should have a self-inflating bag. If a problem with the anaesthesia circuit should occur, the self-inflating bag should be readily available |

Table 3 Recommendations for the use of filters, as detailed by McEwan and colleagues
agonist salbutamol. They comment that death or injury was avoided only by the timely diagnosis of breathing circuit obstruction. Diagnosis of breathing circuit obstruction originating in the filter can clearly be difficult. Both Smith and colleagues, and Aarhus and co-workers warn that this can be confused with bilateral pneumothorax and bronchospasm.1

Williams and Stacey also described a case of rapid airway obstruction which was difficult to differentiate from either pneumothorax or bronchospasm following the onset of pulmonary oedema. These authors warn that even small amounts of proteinaceous fluid in the filter may precipitate this type of critical incident. The risks of tracheal tube obstruction secondary to the use of HMEs for long-term ventilation were highlighted many years ago by Cohen and colleagues.30

The risk of a sudden increase in airway resistance or of airway obstruction, partial or complete, is particularly acute during anaesthesia when filters are concealed beneath drapes or during anaesthesia in the prone position.10 Given the uncertain efficacy of filters and the known problems of filter obstruction, it would seem wiser to exclude the filter in circumstances where both visual and physical access is difficult. In these situations, the circuit should be discarded between patients.

The performance characteristics of different HMEF types are clearly important in terms of breathing circuit patency. In addition to variations in airway resistance intrinsic to the filter as it becomes wetted, HMEs may alter the function and behaviour of attached anaesthetic or ventilator equipment. These changes in performance characteristics induced in adjacent upstream equipment may evolve so subtly that they are difficult to detect. The differences between hydrophobic and hydroscopic HMEs were highlighted in relation to long-term ventilation by Villafane and colleagues who reported increased resistance in tracheal tubes during mechanical ventilation when different humidification devices were used.104

If a HME/filter is not to be used at the patient end of the circuit, it is tempting to protect circle absorber systems from bacterial contamination by incorporating these devices immediately before the absorber. The purpose of this is to utilize the biological filtering function of the device. This tactic does not take into consideration the consequences of the heat and moisture function of the device. Sudden or gradual obstruction of the filter or of adjacent devices is not the only hazard, and HMEs may affect adjacent downstream apparatus also.

### Filters and HMEs, and carbon monoxide production

In certain circumstances, carbon dioxide absorbers degrade all currently available volatile anaesthetics to compounds that are toxic, the most important of which is carbon monoxide. Various authors have reported this effect with desflurane, enflurane, and isoﬂurane, all of which may be degraded to carbon monoxide.11, 13, 16, 40, 41, 60

Long anaesthetic maintenance times are not required for significant carbon monoxide poisoning to occur. Short periods of exposure to desflurane in the presence of desiccated baralyne are potentially lethal. Berry and colleagues reported that after as little as 15 min exposure to this combination, the arterial blood gases of a fit young ASA 1 experimental subject demonstrated the following results: oxygenated haemoglobin (HbO2), 63%; carboxyhaemoglobin (COHb), 36%; and methaemoglobin (MetHb), 1%.16 High levels of COHb are not always required to increase patient morbidity or mortality. Allred and colleagues reported that during graded exercise in patients with coronary artery disease, COHb levels as low as 2.9–4.5% can exacerbate myocardial ischaemia in a dose related manner.3 Unexpected ST segment changes or a turbulent anaesthetic on a Monday morning list may be the only clue to carbon monoxide poisoning.

Tibbles and Perrotta discuss the management of carbon monoxide poisoning and emphasize that a 1 h exposure to 1000 p.p.m. carbon monoxide will produce approximately 25% COHb, sufficient to cause severe neuropsychiatric impairment, whereas 67% COHb causes death.101 Myers and Britten, on the other hand, found a poor correlation between the levels of COHb and the damage incurred to the patient. Some neurological damage can only be demonstrated following cognitive testing and neurobehavioural studies.79 Signs and symptoms of carbon monoxide toxicity are masked during and after anaesthesia. Although COHb cannot be detected by pulse oximetry, it is possible to detect COHb with blood gas analysers if they also have carbon monoxide-oximetry. Where elevated levels of carbon monoxide have been demonstrated, it may be reasonable

<table>
<thead>
<tr>
<th>Complication</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pneumothorax</td>
<td>McEwan,72 Smith93</td>
</tr>
<tr>
<td>Disconnection</td>
<td>Bengtsson,8 Caplan37</td>
</tr>
<tr>
<td>Disable Disconnect Alarm</td>
<td>Milligan,77 Pyne,86 Campbell26</td>
</tr>
<tr>
<td>Increased Airway Resistance</td>
<td>Aarhus,1 Barnes,9 Buckley,24 Stacey,97 Villafane,104 Cohen30</td>
</tr>
<tr>
<td>Obstruction</td>
<td>Barton,10 Australian Therapeutic Device Bulletin,50 Prados,84 Prasad,85 Barnes and Normoyle,9 Walton,105 Williams and Stacey116</td>
</tr>
<tr>
<td>Delayed Induction</td>
<td>Goddard45 Grodin46 Grodin47 Janshon and Dudziak50 Marcus,71 Da Fonseca14</td>
</tr>
</tbody>
</table>
for patients to be followed up for evidence of postoperative cognitive dysfunction. Some would argue that carbon monoxide production in circle absorber systems is a non-problem or is only relevant if prolonged procedures occur. Woehlck warns that this apathetic position may generate significant harm.\textsuperscript{120}

Ianshon and colleagues reported two similar incidents of carbon monoxide production that occurred during induction of anaesthesia with both enflurane and sevoflurane. Delay in induction, over-hot absorber canisters and visible condensate in the tubing were characteristic findings in these cases. The machines had not been in use for 2 weeks.\textsuperscript{60} A common factor with all of these case reports was that the anaesthetic machines were not in regular use, thus enabling desiccation of absorbent to occur with time. All the authors who reported these cases have since changed their clinical practice to ensure fresh absorbent is used at the beginning of each day. As only dry absorbent has been implicated in this reaction, of especial concern is the observation that condensing water was visible in the anaesthetic tubing of the above cases. This indicates that visible condensation is not proof of adequate circuit hydration, contrary to the findings of Beydon and colleagues,\textsuperscript{17} who hold the view that if you can see condensation in the circuit tubing then humidification is adequate.

The source of carbon monoxide in circle systems remained a puzzle for some time until drying of the absorbent was implicated following investigations by various authors including Middleton and co-workers,\textsuperscript{76} who made the original observation, Lentz,\textsuperscript{65} Moon,\textsuperscript{78} and Frink and colleagues.\textsuperscript{41}

Brown and his co-workers have demonstrated that the function of the absorbent is directly related to the degree of hydration.\textsuperscript{23} The water content of circle systems is partly derived from the granules themselves either from residual moisture included at the time of manufacture or through chemical production (1 mol of carbon dioxide produces 1 mol (18 g) of water); or from exhaled moisture from the patient and from re-circulated moisture.

HME/filters are designed to retain exhaled moisture on the patient side of the HMEF. They can only contribute to patient humidification if they are placed in the circuit where to and fro movement of gas occurs, that is at the Y piece. If a HMEF is placed immediately before the absorber in an attempt to reduce bacterial contamination, not only will moisture exhaled from the patient be largely prevented from rehydrating the soda lime, but also the re-circulated moisture from the soda lime itself will be prevented from rehydrating the granules. If the water content of soda lime or Baralyme in particular, is reduced to such an extent that desiccation occurs, carbon monoxide production occurs secondary to degradation of the volatile agents. Degradation is inversely related to absorbent water content. Baxter and Kharasch remind us that the greatest carbon monoxide concentrations occur with desflurane and fully desiccated Baralyme.\textsuperscript{13}

An assumption is made that water production from the reaction between soda lime and carbon dioxide will be sufficient to prevent desiccation during subsequent use. Fang and colleagues showed that drying of absorbent will occur at fresh gas flow rates greater than 3 litre min\textsuperscript{-1}.\textsuperscript{40} These authors investigated carbon monoxide production in relation to anaesthetic agent used, fresh gas flow, and the water content of the absorber and made some recommendations. Their results suggest that carbon monoxide generation can be avoided for all anaesthetics by using soda lime with 4.8% (or more) water or Baralyme with 9.7% (or more) water, and by using inflow rates of less than 2–3 litre min\textsuperscript{-1}. They contend that such inflow rates are low enough to ensure that the absorbent does not dry out. Baxter reported that even lower (minimal) flow rates are required to prevent drying.\textsuperscript{12} Baxter suggested flow rates of <1 litre min\textsuperscript{-1} are required to eliminate this risk. Baum and colleagues take the fresh gas flow even lower and suggest that rates as low as 0.5 litre min\textsuperscript{-1} are required to avoid drying.\textsuperscript{11}

Even with these low flows, the effect of an HME placed between the circuit and the absorber may be to tip the balance in favour of drying. In the absence of knowing how much moisture is present in the absorbent, Woehlck and colleagues suggest that in order to recognize and end patient exposures that occur, despite preventative measures, indirect mass spectrometer monitoring for carbon monoxide should be used during general anaesthesia.\textsuperscript{119} These workers also recommend that anaesthesia technicians and housekeeping personnel should be instructed to turn off all anaesthesia machines after the last case of the day in each room.\textsuperscript{118} This has implications for anaesthetic machines whose oxygen failure alarm is battery operated with a life of 40 h. Alternative strategies may involve the measurement of circuit humidity or inclusion of moisture reservoirs or moisture dye indicators within the circle absorber. A messy prophylactic solution suggested by Woehlck and Kharasch is to dip the absorbent in water before the start of anaesthesia.\textsuperscript{117} However, even under these circumstances, carbon monoxide production may occur unless the water is evenly distributed throughout the canister.

HMEs only contribute to patient humidification if placed on the Y connector between the circuit and the patient, as they depend on to and fro air movement. The relationship between circle absorber systems and HMEs has been investigated to a limited degree. Henriksson and colleagues investigated the effect of inserting HMEs into the Y joint of circuits on circle absorber systems.\textsuperscript{54} They wished to determine if the inherent inadequacy of humidification of these systems at high fresh gas flows (>5 litre min\textsuperscript{-1}) could be compensated. They recommended that at high flow rates, HMEs should be included in the circuit. The flow rates investigated were beyond those commonly used for circle absorber systems in clinical practice. The last measurements were made 60 min after inclusion of the HME, a time when other authors have stated that HMEs are just reaching their steady state. Bissonette and colleagues had demonstrated...
previously that in-line HMEs become more efficient at retaining expired moisture with increasing duration of the procedure, reaching maximum efficiency after 1 h.20

Bisinotto and colleagues investigated the relationship between humidity and tracheobronchial damage. They demonstrated that the intrinsic humidifying action of circle systems at low flow (<2 litre min⁻¹) was adequate at 60 min, but that at flow rates of 5 litre min⁻¹ (very high flow rates) extra humidification was required if a recommended lower limit of absolute humidity greater than 20 mg litre⁻¹ is to be achieved.19 The authors did not measure carbon monoxide production.

The measurement of humidity and the time to a steady state within anaesthetic circuits can be achieved by a number of means including gravimetric hygrometry, dew point hygrometry, wet–dry bulb psychrometry, mass spectrometry, spectroscopic hygrometry, and electrical hygrometry. Kleemann investigated circle absorber humidity by designing a custom-made apparatus suitable for prolonged use under clinical conditions.62 He was able to continuously measure humidity and temperature in the inspired and expired gas mixtures of a breathing circuit. He validated his results against the standard psychrometer technique. He demonstrated that at flow rates below 1.5 litre min⁻¹, an absolute humidity of 21.3 mg H₂O could be achieved after 120 min. Flow rates of greater than 3.0 litre min⁻¹ were found to be too high for maintaining humidity during prolonged anaesthesia. Although his study sought the relationship between fresh gas flow, humidity, and tracheobronchial damage, the results confirm that flow rates through circles should be below 3 litre min⁻¹ to ensure adequate humidification of the respiratory tract. The implication is that flow rates in excess of this cause tracheobronchial drying as a result of drying of the absorber granules. The possible detrimental effects on these results of an HME placed between the circuit and the absorber were not investigated, but the results clearly demonstrate that drying of anaesthetic circuits does occur and that intrinsic water production through the chemical reaction of soda lime and carbon dioxide is inadequate to maintain humidity at higher flow rates.

Flow rates of less than 3 litre min⁻¹ are required to protect the respiratory tract from drying, but what flow rates are required to protect the absorbents from drying out and are they the same? Fang and colleagues have investigated the minimum per cent water in both baralyme and soda lime required to avoid carbon monoxide production.40 These authors state that soda lime containing 4.8% or more water (standard soda lime contains 15% water) generates no carbon monoxide and that the same applies to baralyme with 9.7% (or more) water. They used flow rates of less than 2–3 litre min⁻¹ during this study. Baxter and Kharasch found a minimum safe level of humidity required to avoid desiccation and carbon monoxide production, and established that this could be achieved by adding the full complement (13%) of water to Baralyme.13 The effect of time on drying did not feature in their conclusion. Even if water is added to soda lime at the beginning of a long procedure, Soro and co-workers found, amongst other factors, that drying occurs exponentially with time.96 The time constant is directly proportional to the volume of soda lime contained within the canister and is inversely proportional to the continuous fresh gas flow rate.

The effect of interposing an HME between the circuit and the absorber is unknown but Wilkes and Mecklenburgh demonstrated that the moisture conserving capabilities of filters and HMEs can be calculated from a formula for different fresh gas flows.111 Not all HMEFs are equally efficient. The effect of adding the most efficient HMEFs to circle systems is likely to exacerbate the risk of soda lime desiccation by decreasing the natural replenishment of moisture from the patient’s exhaled gases and the recirculated intrinsic water content of the absorber.

Moon investigated the relationship between drying and carbon monoxide production.28 This author described 31 cases of intraoperative carbon monoxide poisoning during enflurane or isoflurane anaesthesia using circle systems that became desiccated. Some carbon monoxide concentrations exceeded 1000 p.p.m. and COHb levels reached 30% or more. It is clear that at high fresh gas flows, loss of moisture through the expiratory waste gas valve can exceed water production from the reaction between soda lime and carbon dioxide.

Carbon monoxide monitoring is not part of the standard gas analysis on anaesthetic machines but would identify if and when carbon monoxide production occurred. Although both industrial and domestic carbon monoxide monitors are now commonplace and cheap, some are affected by halogens, ammonia, and nitrogen gases. Adding an appropriate device for measuring carbon monoxide to standard anaesthesia monitoring may be an inexpensive option that does not require mass spectrometry.119

Filters and HMEs, and compound A

Compound A (2-(Fluoromethoxy)-1,1,3,3,3-pentafluoro-1-propene) is variously known as a halo-alkene or a vinyl ether, or a vinyl halide. It is one of several products formed when sevoflurane dehydrofluorinates in the presence of strong bases in soda lime and barium hydroxide lime, especially at higher temperatures. Compound A is the most common sevoflurane degradation product in anaesthesia machines. Although these compounds have been demonstrated to be nephrotoxic in mice, their significance in humans remains unknown.

The production of compound A, like carbon monoxide, is related to the dryness (and temperature) of the carbon dioxide absorber granules. Cunningham and colleagues demonstrated that drying Sodasorb from 16 to 11% moisture had little effect on the concentrations of compound A, but drying to 2–6% moisture produced greater concentrations.33
Ruzicka and co-workers found that the release of volatile sevoflurane degradation products in an anaesthesia circuit is highly dependent on soda lime temperatures and water content. Higuchi and colleagues have been working on the production of new carbon dioxide absorber formulations to address the production of these toxic compounds. In the United States, the Food and Drug Administration recommends the use of sevoflurane with fresh gas flow rates of at least 1 litre min\(^{-1}\) for exposures up to 1 h and at least 2 litre min\(^{-1}\) for exposures greater than 1 h in an attempt to reduce exposure by washing the substance from the circuit. These recommendations are empirical and do not relate to some experimental evidence. Interestingly, the fresh gas flow requirements found by some authors for avoiding substance A accumulation (>3 litre min\(^{-1}\)) are in conflict with the requirements for reducing carbon monoxide production (<1 litre min\(^{-1}\)). In addition, Egar and colleagues found that baralyme dehydration increases, and soda lime dehydration decreases, degradation of the inhaled anaesthetic sevoflurane to compound A.

It would seem prudent to investigate the need for inclusion of a carbon monoxide analyser and a compound A analyser amongst gas monitoring equipment if an HME/ filter is used in a circle system. In the absence of direct carbon monoxide monitoring, it is possible to identify if carbon monoxide production is occurring during anaesthesia by measuring the percent of COHb in the patient’s blood. Using current blood gas analysers that incorporate carbon monoxide-oximetry enables this solution but this is not a satisfactory order of events. As we know the humidity required to avoid carbon monoxide production, it may be easier to avoid the potential risk of poisoning from both toxins by measuring and/or controlling humidity.

Filters and HMEs and false elevation of pulse oximetry reading

Aside from the direct damage incurred by carbon monoxide, it has an impact on the interpretation of pulse oximetry. Many anaesthetists may consider that carbon monoxide exposure and intoxication is only a matter of concern when dealing with heavy smokers with ischaemic heart disease, or patients exposed to fires in enclosed spaces. The impact of carbon monoxide on oxygen saturation would not normally enter into consideration in other circumstances. We are lulled into a false sense of security believing that our oximeters truly reflect patients’ \(S_{\text{PO}_2}\) levels. If our patients have been exposed to desiccated absorbers, this confidence may be inappropriate.

Vegfors and Lennmarken investigated the ability of pulse oximeters to measure COHb as HbO and compared results using a co-oximeter. They concluded that pulse oximeters measure COHb as HbO and warn of the dangers of relying on oximetry when COHb is present. Buckley and co-workers found that when significant patient exposure to carbon monoxide has occurred, leading to carbon monoxide poisoning, errors in estimation of \(S_{\text{PO}_2}\) occur. Oxygen saturation, as measured by pulse oximetry, failed to decrease to less than 96% despite COHb levels as high as 44%. Pulse oximetry is unreliable in estimating HbO saturation in patients massively exposed to carbon monoxide and should also be interpreted with caution when used to estimate oxygen saturation in smokers. Barker and Tremper warn that in the presence of COHb, the \(S_{\text{PO}_2}\), is approximately the sum of COHb and HbO, and may seriously overestimate the latter.

These results contrast with the findings of Berry and co-workers who noted a small decrease in \(S_{\text{PO}_2}\), in association with a COHb of 30%, although the decrease in saturation did not reflect the entire increase in COHb. Presumably, these warnings also apply in patients exposed to CO from desiccated soda lime and volatile anaesthetics, where we know we can generate clinically significant levels of carbon monoxide? Until we measure it, we will not know. Unless COHb can be specifically excluded, we do not even know the significance of the \(S_{\text{PO}_2}\). Woehlk roughly estimated that in the USA the possible extent of the number of patients exposed to carbon monoxide as a result of anaesthetic breakdown each year to be approximately 1000—10 000.

At present, without the ability or willingness to measure toxic substance production or humidity, it is important to understand contributory factors to the risk in order to reduce it. Greatest risks are where absorbent drying most commonly occurs such as Monday mornings, following the use of high fresh gas flows (>3 litre min\(^{-1}\)) especially in remote sites, and in outlying hospitals or theatres where general anaesthesia is used occasionally (e.g. ophalmic theatres). It is not sufficient to just look in the theatre log book for the last period of use of an anaesthetic machine. New absorbent should be started at the beginning of the list, each day, and fresh gas flow rates of less than 1 litre min\(^{-1}\) used for maintenance of anaesthesia, provided there is minimal circuit leakage. All gas supplies to anaesthetic machines should be turned off at the end of lists, but not the electricity supply, even at weekends, if oxygen failure alarms are dependant on re-chargeable batteries to function. It would seem prudent not to place a filter with HME characteristics between the circuit and the absorber, but to use a pure biological filter. The impact of incorporating a HME device between the circuit and the absorber has not been investigated in relation to these recommendations. It would seem sensible to clearly differentiate HMEs, HMEFs, and filters, thus enabling the insertion of a filter alone, when required, immediately before the absorber without restricting the circulation of airway humidity.

Delay or failure of gas induction

The work of McGinty and co-workers, Lerman and colleagues, and Paris and colleagues indicates that some patients, especially young adults and children who have
never received chair dental anaesthetics or ether, are opting for a gas induction now that sevoflurane has permitted the reintroduction of this not unpleasant option.73 82 Seropian and co-workers remind us of complications related to prolonged induction which include, but are not limited to, coughing, vomiting, and/or laryngospasm, all of which have an impact on patient morbidity and mortality.91 Delays in coughing, vomiting, and/or laryngospasm, all of which have

inductions when using an Ayres T piece with a filter, and induction. Goddard reported difficulty in performing gas the expiratory limb, resulting in failure or delay in gas

results of using an HME if it facilitates the drying of carbon dioxide absorbers (Table 4). Grodin and co-workers in two separate papers46 47 found that not only does dry soda lime absorb halothane, isoflurane, and enfurane akin to a sponge but also, dry absorber degrades the volatile agent, thus reducing the amount available to the patient, as observed by Janshon and Dudziak60 and Funk.42

Thwaites and co-workers recommend sevoflurane gas induction as a technique of choice in patients with difficult airways.100 Reduction in the inspired concentration of sevoflurane under these circumstances increases the risk of a turbulent induction, as there is prolongation of the second stage. All the consequences of laryngospasm, desaturation, and loss of airway may ensue.

Resistance to flow induced by filters and HMEs is not just a problem of long-term mechanical ventilation, it is also of concern during induction and maintenance of anaesthesia, as is dead space, especially in paediatrics. Wilkinson and co-workers investigated the resistance to flow for 12 hygroscopic HME in order to determine the possible effects on the work of breathing during steady state anaesthesia.114 They found the dead space to be equal to standard catheter mounts (12 ml), and they comment that resistance to breathing was ‘low, compared to other anaesthetic equipment’. The use of some HMEFs in paediatrics has been restricted by the dead space of the devices. Booker reported that the deadspace of the smallest HMEF (45 ml) used in his study had restricted their use to children of greater than 15 kg.22

Even if the dead space permits the use of a filter or HME during induction, the resistance to flow may not. The pressure gradient across a new filter or HME is in the order of 1.0–1.5 cm H2O at fresh gas flows of 50 litre min–1. This gradient is sufficient to allow diversion of fresh gas down the expiratory limb, resulting in failure or delay in gas induction. Goddard reported difficulty in performing gas inductions when using an Ayres T piece with a filter, and this technique34 was the cause of concern for Marcus and colleagues.35 71 Da Fonseca and co-workers recommend that the HME should be removed from the Mapleson F breathing system until inhalation induction is complete, or that the reservoir bag is completely occluded unless an effective seal is obtained with the mask. This problem is the subject of a hazard warning within our own department, and the use of a filter or HME during induction with a T piece has been discontinued. When using your cupped hand at the beginning of a gas induction, no measurable volatile anaesthetic agent reaches the patient, irrespective of the circuit, at fresh gas flows of less than 3 litre min–1. When attempting to hyperoxygenate the patient and using low fresh gas flow rates, gas diversion away from the patient also occurs if the facemask is merely suspended over the patient’s face before induction of anaesthesia. This further reduces the efficacy of this already inefficient manoeuvre. McGowan and Skinner emphasize the importance of a good fit between mask and face during accelerated induction techniques, and this is especially important if a filter or HME is incorporated in the circuit.24 In comparative trials of inhalation induction by Lerman and co-workers,66 Sigston and co-workers,92 and Paris and co-workers92 sevoflurane was compared favourably against halothane. In these paediatric studies HMEFs are conspicuously absent from the detailed descriptions of the induction techniques used.

Filters and HMEs as a disconnection hazard

Adams, in a symposium on mishap or negligence, emphasized that disconnections occur most frequently at the site of connection of the tracheal tube to the breathing system. Adams cited a survey of members of the Canadian Anaesthetists’ Society, in which 63% of the respondents stated that such disconnections occurred at least ‘occasionally’ at the tracheal tube connection, and that such disconnections occur so often as to be considered as routine.2 In an analysis by Caplan and co-workers of closed claims that had resulted in death or permanent disability, disconnection at the junction between the distal end of the breathing circuit and the tracheal tube accounted for 16% of cases (Table 4).27 For head and neck and similar surgery, adding filters to a circuit constitutes an additional disconnection hazard by introducing an extra connection. This is despite the requirement for manufacturers to comply with the International Standard for HMEs (ISO 5356-1: 1987), associated with tapered 15 and 22 mm connections.108

The disconnection hazard is exacerbated when the filter is bulky, angular, within the surgeons operating environment, and concealed by drapes. An increased risk is evident for both spontaneously breathing patients and patients receiving IPPV. Russell and co-workers reviewed the first 2000 incidents reported to the Australian Incident Monitoring Study and found 317 incidents which involved problems with ventilation.89 Eighty-nine per cent of problems were related to circuit disconnects or misconnects, of which 48% were disconnections. During IPPV, detection of patient disconnection from the circuit is not necessarily guaranteed by the use of low pressure disconnect alarms. Monitor detection was by a low circuit pressure alarm in 37%, but this alarm failed to warn of non-ventilation in 12 incidents. In one-third of the cases, disconnection was associated with interference to the anaesthetic circuit by a third party, and in nearly half with surgery on the head and neck.
Milligan warns of the dangers of disconnect alarms that are disabled by the presence of an HME. Others have investigated failure of disconnection alarms in the presence of HMEs. Pryn and Crosse investigated the relationship between the pressures generated in breathing systems during the inspiratory phase of positive pressure ventilation and devices attached to the circuit. The increased airways resistance associated with the configuration of circuit attachments, especially HMEs, enabled increases in airway pressure between the HME and the ventilator. These increases in pressure were detected by the low-pressure alarm as normal ventilatory cycles. Nine different heat and moisture exchanges were compared in the same breathing system. Those with 15-mm male connectors generate the highest pressures on disconnection (1.1 kPa), sufficient to stimulate the disconnect alarm. They warn that low-pressure alarms should be adjusted to the circuit and ventilator configuration.

The problem was reinvestigated several years later by one of these original authors and it was found that the situation had deteriorated further. Bengtsson and Johnson reported two cases of ventilator disconnection resulting from defective HME (Table 4). Collins and Vaghadia warn that during spontaneous ventilation, incorporating the gas analyser port in the filter housing obscures disconnection from the anaesthetic gases, with a risk of intraoperative awareness. Disconnection from the breathing circuit at a site distal to the gas sampling line, renders $P_{E}^{\text{CO}_2}$ unreliable for detecting circuit disconnection. When disconnection occurs between the filter and the circuit during spontaneous ventilation, the carbon dioxide waveform is still present, rendering a false sense of security. We might assume that other components of the gas monitor would detect this event and warn us that disconnection has occurred, but we generally rely on an audible signal. Aside from observing changes in the bag movement, circuits not monitored by inspiratory and expiratory gas volumes will provide no clues. Monitor manufacturers' default settings for inspired $N_2O$ and volatile agents are $-1$ or $0$. For inspired oxygen, it is $18\%$ for most manufacturers bar one, at $30\%$. These default settings mean that no audible alarm will alert the anaesthetist to this type of disconnection. Kennedy and French report just such an incident. Disconnection between the circuit and the filter during spontaneous ventilation is best monitored electronically by detecting changes in expired gas volume within the circuit. Expired volume measurements are only available for circle systems. There is therefore a risk of intraoperative awareness unless the $P_{E}^{\text{CO}_2}$ records directly from the circuit, rather than for the filter or HME housing. Several manufacturers make co-axial circle systems that incorporate gas analysis tubing in their structure, or incorporate a sampling port on the Y connector of the circuit. There is no reason that similar tubing could not be incorporated in both non-circle systems and parallel circle circuits. An opportunity exists for manufacturers to produce rounded filter housing without a gas analyser port to reduce some elements of this hazard.

**End-tidal carbon dioxide estimation**

When asked the hypothetical question ‘Which monitor would you retain if you were allowed to retain only a single monitor?’ most anaesthetists choose the carbon dioxide monitor. Hardman and co-workers measured the end-tidal carbon dioxide values on either side of breathing filters. They found that the $P_{E}^{\text{CO}_2}$ was significantly lower at the machine side of the filter in both ventilated and spontaneously breathing groups ($P=0.00001$). The measurement error induced by the inclusion of the breathing system filter was significantly greater in spontaneously breathing patients ($P=0.0004$). The source of the error is presumably as a result of the small pressure gradient across the filter membrane. Expired gases mix with some fresh gas on the machine side of the filter, whereas on the patient side, the sample is of pure expired gases. Although not a major hazard of using a filter, this effect may be clinically significant in certain situations such as raised intracranial pressure. During carbon dioxide insufflation for laparoscopic surgery, interpretation of the end-tidal carbon dioxide is further confounded by intra-peritoneal insufflation of carbon dioxide. This problem is not averted by changing the site of the gas analyser port but by avoiding the use of a filter in these circumstances.

Cruz and co-workers expressed disquiet at the practice of estimating arterial carbon dioxide pressure ($P_{a}^{\text{CO}_2}$) by capnography during laparoscopic surgery in pregnant women, as a result of studies on pregnant ewes. During carbon dioxide insufflation, there was evidence of both maternal and fetal acidosis if $P_{E}^{\text{CO}_2}$ was used to guide ventilation. Amos and co-workers concluded from the retrospective analysis of the anaesthetic records of seven pregnant patients who underwent laparoscopic surgery, that caution should be used in interpreting end-tidal carbon dioxide when considering non-obstetric laparoscopic surgery in pregnant women. Bhavani-Shankar investigated the possible consequences of this observation and he and his colleagues have disputed the significance of these findings. Nonetheless, the use of filters when arterial carbon dioxide levels are critical should be considered carefully.

**Conclusions**

Newer filters and HMEs are highly effective, and while many are more efficient than required for protection against standards for biohazard protection, they are not all equally efficient. It would seem that the use of HMEs and filters is not always indicated and they should not be used indiscriminately. Including a filter or an HME in a circuit has a
potentially significant impact on morbidity and mortality. The efficacy of all filters is not fully established. Their ability to clearly reduce the incidence of transmission of infection in clinical studies may not match up to their performance in the laboratory. Until the filtration efficiency of all filters is published against a known standard, there can be no conclusion to this problem. Not all the potential hazards of incorporating filters and HMEs in anaesthetic circuits have been fully explored. The contribution of an HME as opposed to a pure filter in creating a microenvironment in circle absorber systems that predisposes to accumulation of carbon monoxide and other toxic metabolites has not been fully investigated.

HMEs and filters are a hazard during gas induction either directly through gas diversion or indirectly through absorber desiccation. They render pointless the use of non-applied masks for pre-oxygenation of routine cases, except at high fresh gas flows. They should not be used in the presence of active humidification, nebulized drugs, copious secretions, or pulmonary oedema. They should be clearly visible and accessible at all times in order to detect contamination, obstruction, or disconnection. There is an argument for not incorporating the gas analyser port in the filter, but rather incorporating it into the circuit. Filters constructed with a smooth contour in a clear housing are preferable to angular constructions if a disconnection hazard is to be reduced. If you cannot see the filter, there is a strong argument not to use one. When there is a relative or absolute contraindication to filters, they should be omitted and the circuit should be discarded between cases, irrespective of cost.

Industrial protective masks and air purifying filters are clearly identified by name and colour, specific to their purpose. A clearly identifiable distinction between a filter and an HME or an HMEF with or without bacterialic properties, would be useful so that their separate and distinct functions can be used appropriately. Some manufacturers have moved in this direction. The biological filtration capability for particles, bacteria and viruses, in both wet and dry suspension should be clearly apparent. Dynamic changes in function in terms of changes in resistance with saturation, and duration of effective usage should be included in the product insert, as should the humidification efficiency at different flow rates. For longer procedures, some mechanism to indicate the degree of membrane saturation or transmembrane pressure gradient would be useful. The internal dead space and the nature of the HME in terms of whether it is hydrophobic, hydroscopic, and electrostatic or a pleated micropore type would also be helpful, as would the specific indications for choosing one device over another.

References
9 Barnes S, Normoyle D. Failure of ventilation in an infant due to increased resistance of a disposable heat and moisture exchanger. *Anesth Analg* 1996; 83: 193
22 Booker PD. Equipment and monitoring in paediatric anaesthesia. *Br J Anaesth* 1999; 83: 78–90

Campbell RM, Sheikh A, Crosse MM. A study of the incorrect use of ventilator disconnection alarms. Anaesthesia 1996; 51: 369–70


Cruz AM, Sutherland LC, Duke T, Townsend HGG, Ferguson JG, Crane LAA. Intra-abdominal carbon dioxide insufflation in the pregnant ewe. Anesthesiology 1996; 85: 1395–402


du Moulin CG, Saubermann AJ. The anaesthesia machine and circle system are not likely to be sources of bacterial contamination. Anesthesiology 1977; 47: 353–358


Frink EJ jr, Nogami WM, Morgan SE, Salmon RC. High carboxyhemoglobin concentrations occur in swine during desflurane anesthesia in the presence of partially dried carbon dioxide absorbents. Anesthesiology 1997; 87: 308–16


Garibaldi RA, Brit MR, Webster C, Pace NL. Failure of bacterial filters to reduce the incidence of pneumonia after inhalation anaesthesia. Anaesthesiology 1981; 54: 364–8


Goddard JM, Bennett HR. Filters and Ayre’s T-piece. Anaesthesia 1996; 51: 605


Han JN, Liu YP, Ma S, et al. Effects of decreasing the frequency of ventilator circuit changes to every 7 days on the rate of ventilator-associated pneumonia in a Beijing hospital. Resp Care 2001; 46: 89–6

Hardman JG, Curran J, Mahajan RP. End-tidal carbon dioxide measurement and breathing system filters. Anaesthesia 1997; 52: 646–8


Henriksson BA, Sundling J, Hellman A. The effect of a heat and moisture exchanger on humidity in a low-flow anaesthesia system. Anaesthesia 1997; 52: 144–9

Hess D. Filters and anesthesia breathing circuits: can we cut costs without harm? J Clin Anesth 1999; 11: 531–3


Hogarth I. Anaesthetic machine and breathing system contamination and the efficacy of bacterial/viral filters. Anaesth Intens Care 1996; 24: 154–63


Kleemann PP. Humidity of anaesthetic gases with respect to low flow anaesthesia Anaesth Intens Care 1994; 22: 396–408


Lerman J, Davis P, Welborn L, et al. Induction, recovery, and safety characteristics of sevoflurane in children undergoing...
ambulatory surgery: a comparison with halothane. Anesthesiology 1996; 84: 1322–40


Milligan KA. Disablement of a ventilator disconnect alarm by a heat and moisture exchanger. Anaesthesia 1992; 47: 279


Seropian MA, Robins B. Smaller than expected sevoflurane concentrations using the sevotec 5 vaporizer at low fill states and high fresh gas flows. Anesth Analg 2000; 91: 834–6


Stevens J. Breathing system filters. Anaesthesia 1999; 54: 90


Vezina DP, Trepanier CA, Lessard MR, Gourdeau M, Tremblay C. Anesthesia breathing circuits protected by the DAR Barrierbac S breathing filter have a low bacterial contamination rate. Can J Anaesth 2001; 48: 748–54


Wilkes AR, Ferguson RA, Mecklenburgh JS. Ability of breathing system filters to prevent liquid contamination of breathing systems. Br J Anaesth 1998; 80: 550


Wilkes AR. Measuring the filtration performance of breathing system filters using sodium chloride particles. Anaesthesia 2002; 57: 162–8
Wilkes AR. Mecklenburgh JS. Predicting the moisture-conserving performance of breathing system filters with different anaesthetic breathing systems. Br J Anaesth 1997; 79: 681–2


Wilkes AR. The ability of breathing system filters to prevent liquid contamination of breathing systems: a laboratory study. Anaesthesia 2002; 57: 33–9


Wille B. Hygiene measures for anaesthesia and ventilator equipment. Krankenhaus-HygienenInfektionsverhutung 1989; 11: 17–21


Woehlck H, Kharasch ED. Carbon dioxide absorber moisture content. Anesthesiology 1997; 87: 1590–1

Woehlck HJ, Dunning M 3rd, Connolly LA. Reduction in the incidence of carbon monoxide exposures in humans undergoing general anesthesia. Anesthesiology 1997; 87: 228–34


Woehlck HJ. Severe intraoperative CO poisoning: should apathy prevail? Anesthesiology 1999; 90: 353–4