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Clarifying the role of activated charcoal filters in preparing an anaesthetic workstation for malignant hyperthermia–susceptible patients

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SUMMARY

Malignant hyperthermia (MH) is a life-threatening condition caused by exposure of susceptible individuals to volatile anaesthetics or suxamethonium. MH-susceptible individuals must avoid exposure to these drugs, so accurate and reproducible processes to remove residual anaesthetic agents from anaesthetic workstations are required. Activated charcoal filters (ACFs) have been used for this purpose. ACFs can reduce the time for preparing an anaesthetic workstation for MH patients. Currently, the only commercially available ACFs are the Vapor-Clean™ (Dynasthetics, Salt Lake City, UT, USA) filters which retail at approximately AUD$130 per set of two, both of which are to be used in a single anaesthetic. Anaesthetic workstations were saturated with anaesthetic vapours and connected to a Miran ambient air analyser (SapphIRe XL, ThermoScientific, Waltham, MA, USA) to measure vapour concentration. Various scenarios were tested in order to determine the most economical configurations of machine flushing, component change and activated charcoal filter use. We found that placement of filters in an unprepared, saturated circuit was insufficient to safely prepare an anaesthetic workstation. Following flushing of the anaesthetic workstation with high-flow oxygen for 90 seconds, a circuit and soda lime canister change and the placement of an ACF on the inspiratory limb, we were able to safely prepare a workstation in less than three minutes. A single filter on the inspiratory limb was able to maintain a clean circuit for 12 hours, with gas flows dropped from 10 lpm to 3 lpm after 90 minutes or removal of the filter after 90 minutes if high gas flows were maintained.

Key Words: anaesthetic machine, malignant hyperthermia, activated charcoal filter

The introduction of anaesthetic workstations with complex internal circuitry has made elective preparation for patients with known or suspected malignant hyperthermia (MH) less straightforward. A study by McGraw and Keon showed that an older generation workstation could be considered safe after a 15-minute flush and a circuit plus soda lime change[1]. The modern anaesthetic workstation has many internal plastic and rubber parts which can absorb and release anaesthetic vapours[2]. Compartmentalised internal circuitry which may not be refreshed by high gas flows and a complex gas flow circuit for ventilation may also account for slow washout times of anaesthetic vapours from the modern workstation[3,4].

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Useful studies have been performed to characterise the washout of volatile agent from these more complex workstations[4–8]. To adequately prepare a workstation to the only currently studied safe limits of volatile concentration (<5 ppm)[9], times of over 100 minutes have been recommended[10].

Charcoal has been suggested as a method for removing volatile agents from an anaesthetic workstation[11]. Commercially produced charcoal filters have been shown to be effective in reducing the time needed to prepare a workstation[12,13] but there have been some assumptions and extrapolations in relation to changing of filters and flow rates that have not been studied. Some of these publications were not entirely independent from the manufacturer of the filters. Although charcoal filters are not yet approved for use in Australia, they have been approved by the Food and Drug Administration in the USA and Medsafe in New Zealand and are in regular use in these countries.

In particular, the questions unanswered in the available literature are, if we are using filters to decrease preparation time:

1. Do we need to change the filters every hour?
2. Do we need to flush the circuit prior to filter installation?
3. Do we need to replace the circuit and soda lime?

These questions are important from both an economic standpoint and from a safety perspective.

The possibility of time pressures in the modern operating theatre environment (with its limited resources and high demand) leading to inadequate preparation of workstations is always a concern. Adoption of a universal protocol for all workstations would be ideal for trainees and consultants working across different institutions and indeed countries. An alternative would be to consider the storage and maintenance of a dedicated anaesthetic workstation for patients susceptible to MH, but the input and cost of undertaking this may be prohibitive.

In our hospital, where we perform many biopsies per year for MH, the economic implications of prolonged flushing and high gas flow rates versus use of charcoal filters become more relevant. Keeping the guidelines simple, reducing the variability of practice and minimising the time spent in preparation could all add to the safety and efficiency of MH preparedness.

Our technical study helps to assess how the filters can be used, whether they need to be replaced (if at all) and the time taken to prepare a workstation using the filters. It also addresses the rebound phenomenon in relation to the use of charcoal filters.

METHODS

All experiments were performed on Datex-Ohmeda Aisys® anaesthesia workstations (GE Medical, Madison, WI, USA). Four different workstations were used for this study to ensure variability of equipment did not impact on results. We prepared our workstations for the experiments by contaminating them with anaesthetic gas. The workstations were contaminated by switching the ventilation circuit on for two hours, ventilating a test lung with a tidal volume of 500 ml and a respiratory rate of 10/minute with an I:E ratio of 1:2. For isoflurane we used 1.5%, desflurane 6.0% and sevoflurane 2.0% to contaminate the circuit. Fresh gas flow was set at two litres per minute (lpm). This was the contamination technique employed in previous studies[8].

We obtained Vapor-Clean™ activated charcoal filters (Dynasthetics LLC, Salt Lake City, UT, USA) and used them in a variety of configurations in our study. Each filter contains 50 ml of granular activated charcoal between spun-bond polypropylene filter mesh. Filters were either placed on the inspiratory limb, expiratory limb or both limbs of the breathing circuit, attached between the anaesthetic workstation and the circuit.

To detect the presence of anaesthetic gases, we utilised a Miran ambient air analyser (SapphIRe XL, Thermo Scientific, Waltham, MA, USA). The analyser was calibrated according to the manufacturer's guidelines before every experiment. The sampling wand was connected between the

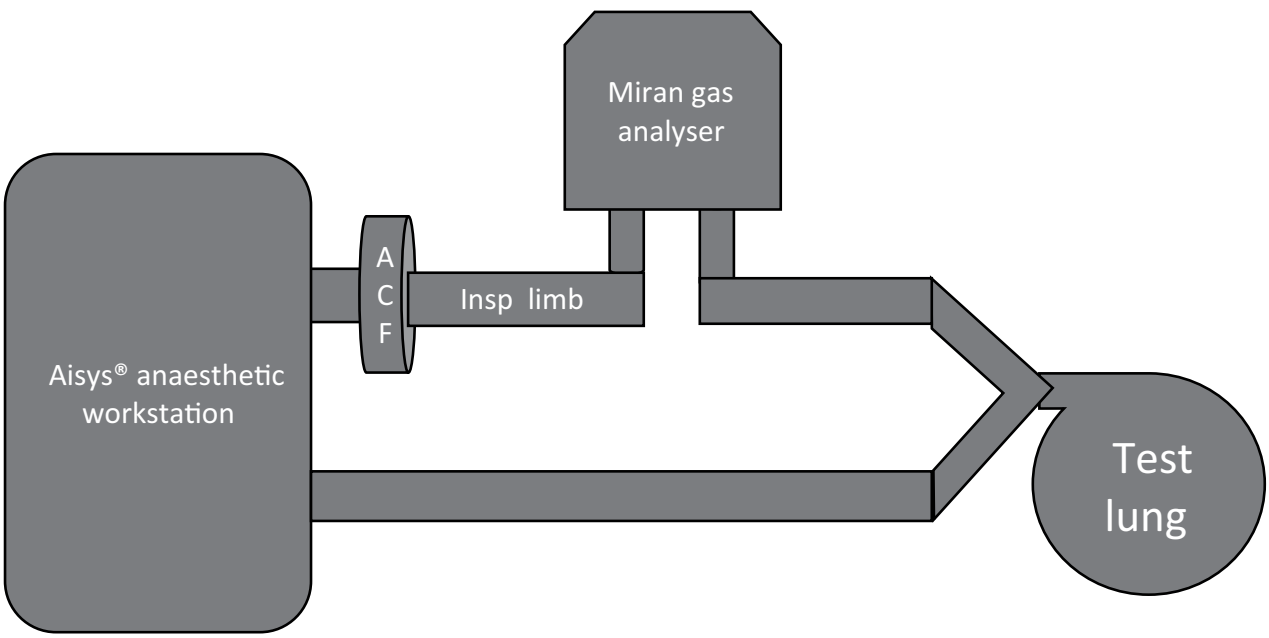

Figure 1: Diagram of anaesthetic circuit with the Miran gas analyser in series. ACF=activated charcoal filter.

filter and the breathing circuit's inspiratory limb (Figure 1). The analyser was zeroed to room air according to manufacturer instructions. For all three anaesthetic gases the analyser had an upper limit accuracy of 100 ppm and a lower limit sensitivity of 0.04 ppm, with a reading accuracy of ±10% (manufacturer specification). Analyser sampling was recorded every 60 seconds throughout all experiments. All experiments undertaken were repeated at least once and data presented are typical of results collected.

Experiment 1—Placement of filters with no circuit change

Following contamination of the anaesthetic workstation with desflurane, two activated charcoal filters (ACFs) were inserted (one on each limb of the anaesthetic circuit) and the sampling wand inserted. No flushing or equipment change was undertaken, though the vapouriser was removed. The desflurane concentration was then measured over a 60 minute period following placement of the ACFs.

Experiment 2—Insertion of one ACF and a circuit/soda lime change and oxygen flush with the filter subsequently removed after 90 minutes

Following contamination, the vapouriser was removed and the anaesthetic workstations were flushed with 10 lpm 100% oxygen for 90 seconds with ventilation continued. The circuit tubing and soda lime canister were changed for uncontaminated equipment. An ACF was placed on the inspiratory limb of the circuit and the sampling wand was connected. The whole of this process took less than three minutes. Anaesthetic vapour concentration in the circuit was subsequently measured for 90 minutes, the ACF was then removed, and a further 30 minutes of data were collected, with the fresh gas flow of 10 lpm maintained.

Experiment 3—Insertion of one ACF and a circuit/soda lime change and flush, then flows dropped after 90 minutes

Following contamination, the vapouriser was removed and the anaesthetic workstations were flushed for 90 seconds with 10 lpm, 100% oxygen with ventilation continued. The circuit and soda lime canister were then changed for uncontaminated equipment. An ACF was placed on the inspiratory limb and the sampling wand was connected. The process of flushing and equipment change/ACF insertion took less than three minutes. Anaesthetic vapour concentration was then measured for 90 minutes with the fresh gas flow maintained at 10 lpm. Fresh gas flow was subsequently reduced to 3 lpm. A further 630 minutes (10.5 hours) of data were collected with the ACF still in situ.

Experiment 4—The insertion of one ACF on the expiratory limb and a circuit/soda lime change and flush

Following contamination, the vapouriser was removed and the anaesthetic workstations were

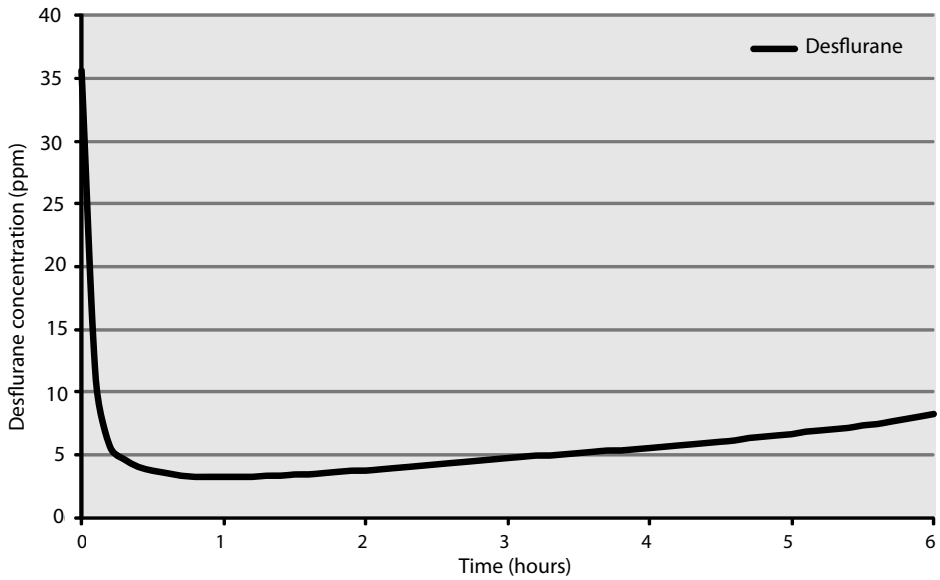

Figure 2: Desflurane vapour concentration in the anaesthetic circuit following saturation of the circuit with vapour for two hours and the subsequent addition of two activated charcoal filters.

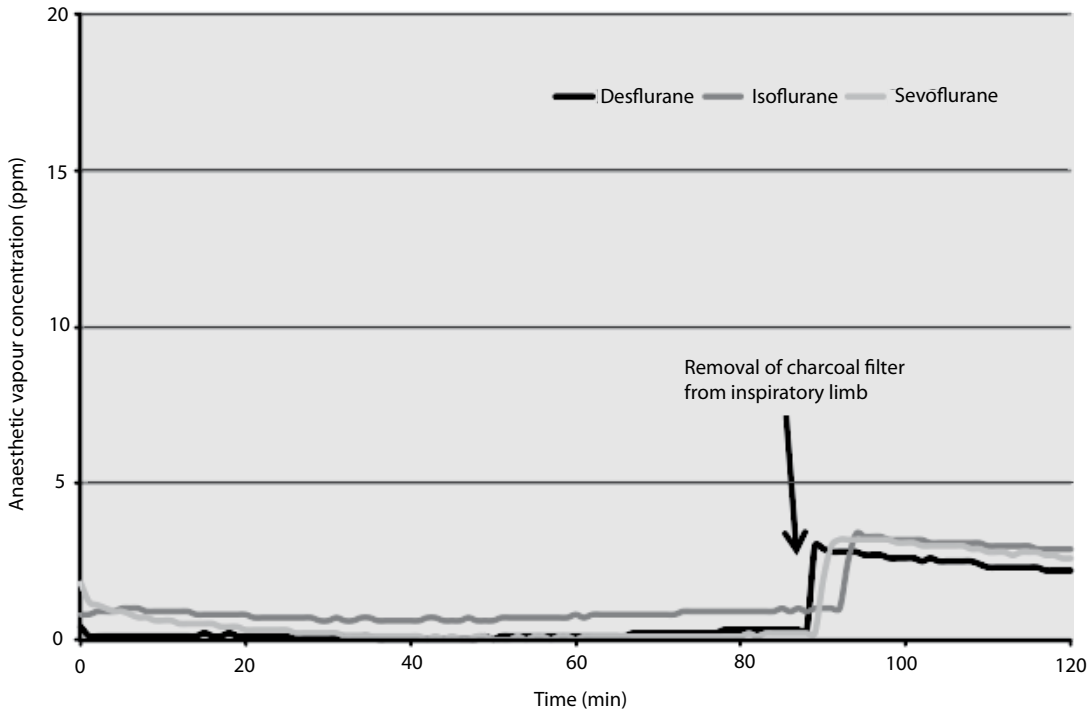

Figure 3: Anaesthetic vapour concentration in the anaesthetic circuit following saturation of the workstation, flushing of the circuit for 90 seconds with high flow oxygen, changing of the circuit and soda lime canister, and insertion of a single activated charcoal filter on the inspiratory limb. The filter was removed after 90 minutes while high flow oxygen delivery was maintained (10 lpm).

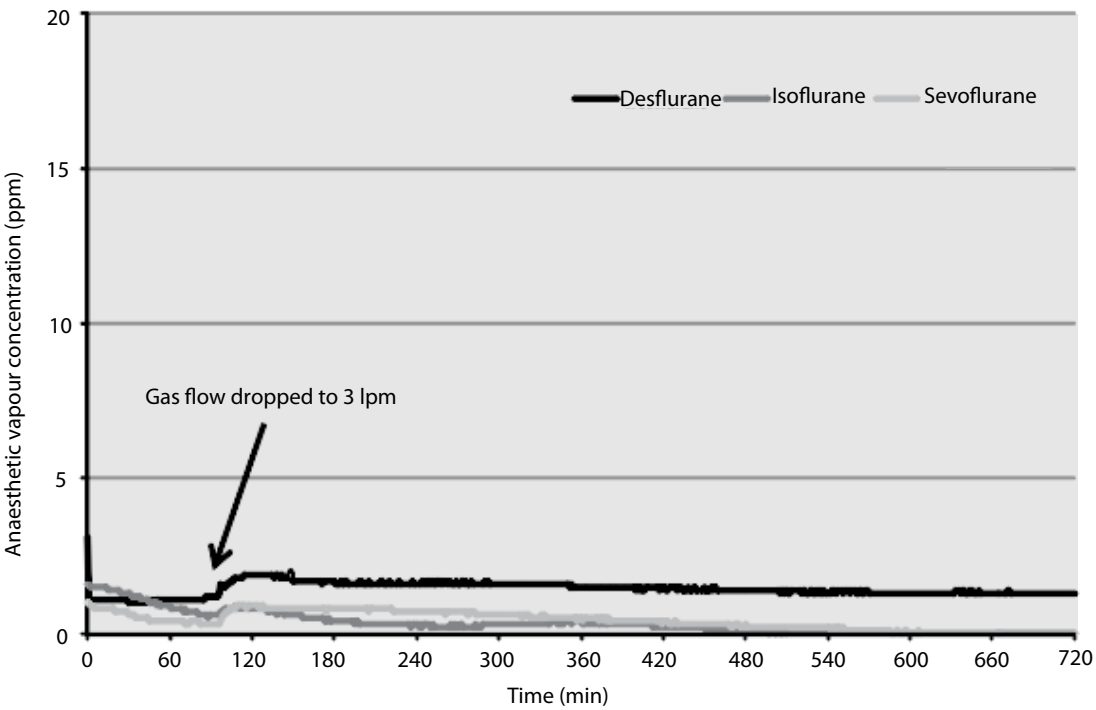

Figure 4: Anaesthetic vapour concentration in the anaesthetic circuit following saturation of the workstation, flushing of the circuit for 90 seconds with high-flow oxygen, changing of the circuit and soda lime canister, and insertion of an activated charcoal filter on the inspiratory limb. Gas flows were reduced after 90 minutes from 10 lpm to 3 lpm with the filter remaining in situ.

flushed for 90 seconds with 10 lpm 100% oxygen with ventilation continued. The circuit and soda lime canister were then changed for uncontaminated equipment. An ACF was placed on the expiratory limb and the sampling wand was connected. The process of flushing and equipment change/ACF insertion took less than three minutes. Anaesthetic vapour concentration was then measured for 90 minutes with the fresh gas flow maintained at 10 lpm.

Data were collected on the analyser and transferred to a Microsoft Excel spreadsheet for collation and graphical representation.

RESULTS

Experiment 1

Figure 2 shows the result of placement of charcoal filters on both inspiratory and expiratory limbs of an anaesthetic workstation contaminated with desflurane, without any prior flushing or change in circuitry or soda lime (though the vapouriser was removed). At the time of placement of filters, the desflurane was switched off and the gas flow was increased to 10 lpm with 100% oxygen. As illustrated, the desflurane concentration dropped to below 5 ppm within three minutes. However, a rebound effect occurred, with desflurane levels rising above 5 ppm after 32 minutes, giving a 29-minute window of ventilation with acceptable levels of exposure to anaesthetic vapour.

Experiment 2

Figure 3 illustrates the vapour concentration of desflurane, isoflurane and sevoflurane following a 90 second flush with 10 lpm 100% oxygen, a change in the anaesthetic circuit/soda lime, removal of the anaesthetic vapouriser and the application of a single charcoal filter to the inspiratory limb of the anaesthetic circuit. As stated previously, from beginning of flush to end of circuit change and sampling wand insertion took no more than three minutes. The results show that at the beginning of detection (three minutes after the beginning of flush) the levels of all three anaesthetic gases had dropped to less than 5 ppm. This was maintained throughout the entire experiment. After 90 minutes the charcoal filter was removed from the inspiratory limb and a fresh gas flow of 10 lpm 100% oxygen was maintained. In all three cases illustrated in Figure 3, the anaesthetic vapour concentrations rose by 2 to 3 ppm but never rose above 3.4 ppm (isoflurane).

Experiment 3

Figure 4 shows the use of a charcoal filter attached to the inspiratory limb over a 12-hour period. Experiments have previously shown that lower fresh gas flows lead to a rise in vapour concentration. We therefore wanted to study the efficacy of a single charcoal filter following 90 minutes of exposure to 10 lpm fresh gas flow. As in the previous experiment, the contaminated circuit was flushed for 90 seconds, the vapouriser was removed, the circuit was changed for a clean anaesthetic circuit and soda lime canister, and an ACF was inserted on the inspiratory limb. Sampling detection began immediately after the circuit change and in all three cases the vapour concentration was below 5 ppm from time of detection. After 90 minutes, the fresh gas flow was reduced to 3 lpm. All three experiments show a rise of 0.3 to 0.7 ppm in vapour concentration following a decrease in flow, but no vapour concentration ever rose above 2 ppm.

Experiment 4

Figure 5 illustrates the effect of placing an ACF on the expiratory limb of the anaesthetic circuit. Following flushing and circuit change, it took at least 35 minutes to reduce the desflurane concentration to below 5 ppm. It was therefore decided that this would be an impractical method for preparing a workstation for anaesthesia.

DISCUSSION

In this study we considered how quickly and safely an anaesthetic workstation could be prepared for a patient known to be susceptible to MH, how long the charcoal filters could be used and the cost implications of utilising charcoal filters in preparing the anaesthesia workstations. With previous studies recommending the use of two charcoal filters in an anaesthetic circuit[12], the cost of preparing an anaesthetic workstation for use with MH-susceptible patients can be high. Currently, a pair of charcoal filters retail at approximately A$130, a carbon dioxide–absorbing soda lime canister retails at approximately $45, and disposable anaesthetic circuits cost approximately $10 to $15 per circuit. With current manufacturer guidelines, preparing an anaesthetic workstation for an MH-susceptible patient would cost approximately $190, with approximately 65% of this as a direct result of the cost of the charcoal filters alone. In healthcare centres where patients with MH are routinely anaesthetised, either for muscle biopsies for diagnostic purposes or for unrelated diseases, a cost of this magnitude may discourage the use of these charcoal filters and favour a more time-consuming machine-flushing method. A reduction in the cost of preparing a workstation fit for an

MH patient from $190 to $125 (a saving of $65 or approximately one-third) by using only one activated charcoal filter per patient would therefore be of some benefit, making the use of these filters more feasible on a regular basis for such institutions.

Figure 2 (Experiment 1) shows that introduction of ACFs on both limbs in a circuit which has not been flushed or changed would not be sufficient to reduce the anaesthetic vapour concentration to below 5 ppm for longer than 30 minutes. If it were an absolute emergency with no circuit or soda lime equipment immediately available but the filters were at hand, one may consider this possibility combined with some sort of pre-flush of the anaesthetic circuit. However, this would be a very short-term solution, with the need for a new circuit, soda lime canister and charcoal filter to be replaced within 30 minutes. We would therefore advise against this practice altogether and recommend an extra three minutes to change the circuit and soda lime absorber (which should be readily available in all anaesthetic departments). This will give certainty in preventing exposure to potentially unsafe levels of anaesthetic vapour. It is of note that it has been implied that the use of activated charcoal filters alone in contaminated anaesthetic circuits without a flush or circuit change is sufficient to reduce exposure of anaesthetic vapours in MH patients[14]. Our results from Experiment 1 suggest that this would not be a safe practice in an Aisys® workstation.

Results (using an Aisys® anaesthetic workstation) from Experiments 2 and 3 show that over a 12-hour period (Experiment 3, Figure 4), a single charcoal filter on the inspiratory limb with a fresh gas flow of 3 lpm after the first 90 minutes is sufficient to keep anaesthetic vapour concentrations to less than 5 ppm. A previous study by Birgenheier et al (using a Dräger workstation) recommended the placement of two charcoal filters, one on the inspiratory and one on the expiratory limb of the anaesthetic workstation, for three reasons[12]. First, it can be difficult to tell which limb is inspiratory and in the confusion it may be placed on the wrong limb. Second, if the expiratory limb valve is not patent or fresh gas flow is less than the minute ventilation, anaesthetic vapours may be inhaled through the expiratory limb. Third, by placing two filters there is twice the amount of charcoal in the circuit, which therefore reduces the risk of a rise in anaesthetic vapour concentration above 5 ppm, especially in patients where MH is detected *de novo* intraoperatively. Our study has reinforced that, technically, two filters are not required in the preparation of a machine for the purposes of elective non-triggering anaesthesia and that this may be relevant in an institution such as ours where we may have occasion to use the filters for

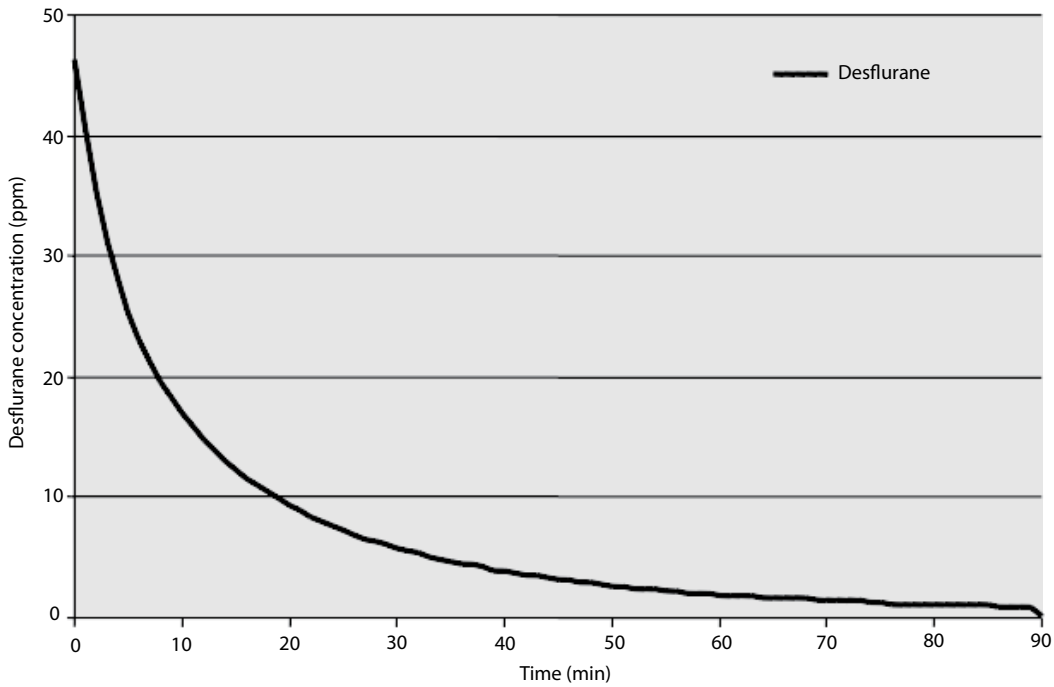

Figure 5: Desflurane vapour concentration in the anaesthetic circuit following saturation of the workstation, flushing of the circuit for 90 seconds with high-flow oxygen, changing of the circuit and soda lime canister, and insertion of an activated charcoal filter on the expiratory limb.

up to 100 cases per year. We acknowledge that filters on both limbs of the circuit represents a very safe practice for those institutions that do not routinely anaesthetise MH patients.

The manufacturer of the Vapor-Clean™ charcoal filters recommends that two filters can be used for up to 12 hours, based on a simple bench test involving a calculation of the absorptive capacity of the charcoal filters[14]. Our data from Experiment 3, Figure 4 shows that one filter will work convincingly for up to 12 hours when placed on the inspiratory limb of the circuit.

In Birgenheier et al, the data presented shows that all workstations currently commercially available were able to achieve an anaesthetic vapour concentration of less than 5 ppm within 90 minutes (24 to 84 minutes)[12]. Other published studies suggest a washout time of up to 104 minutes[10]. In the study by Jones at al[8], the Aisys® workstation took up to 90 minutes to flush. We therefore wanted to know whether, if we removed the filter at 90 minutes and kept the fresh gas flow at 10 lpm, we could actually maintain a safe level of anaesthetic vapour concentration (<5 ppm). As illustrated in Figure 3, Experiment 2, all anaesthetic vapours had been reduced to safe levels by 90 minutes, the filter could be safely removed and ventilation using flows of 10 lpm continued. We surmise that the removal of anaesthetic vapours from the ventilation system would most likely have been as a result of 90 minutes of continued flushing by high fresh gas flows, but it is also likely that the charcoal filter would have contributed to the washout by actively absorbing the vapours and removing them from the system. This provides an alternative pathway to long-term ventilation during anaesthesia should the filter require removal—for example, if charcoal dust was being released into the anaesthetic circuit, a potential risk described on the manufacturer's accompanying fact sheet, or if there was a build-up of water vapour in the circuit. Of note, previous research into activated charcoal has demonstrated that the presence of water vapour has little effect on its adsorptive capacity[15]. We suggest that it would be reasonable to extrapolate our results and assume that a charcoal filter used as described in Experiments 2 and 3 could be removed after the recommended flush time for each specific workstation.

From our experiments, it is clear that ACFs must be placed on the inspiratory limb in order to be effective. Placement of the ACF on the wrong limb would be ineffective and potentially disastrous (see Figure 5). Therefore, when utilising one filter as we suggest, every effort must be made to ensure that it is placed on the inspiratory side of the circuit. If there is any doubt, two ACFs should be used with placement on both limbs in order to eliminate this risk.

It should be noted that all of our efforts were to reduce anaesthetic vapour concentrations to less than 5 ppm. We chose this figure because it had been used in the studies we were analysing and seeking to clarify. We acknowledge that 5 ppm is a figure derived from experiments with pigs known to be susceptible to porcine stress syndrome (the pig equivalent of MH)[9], which may or may not be appropriate to apply to humans who are susceptible to MH. It is, however, the only scientific measure we currently have. Other authors have published their opinion, based on data from muscle biopsies, that levels of up to 50 ppm are safe for MH patients[16].

CONCLUSION

In conclusion, charcoal filters are an effective way to reduce the time taken to prepare a modern anaesthetic workstation for a patient known to be susceptible to MH. One can use one filter in the inspiratory limb for 90 minutes then remove the filter but continue with fresh gas flows of 10 lpm, or one can use one filter in the inspiratory limb and reduce gas flows to 3 lpm after 90 minutes, as long as the filter remains in the circuit. This is effective for at least 12 hours. If one filter is used, it must be confirmed that this is on the inspiratory limb, as it will not be effective on the expiratory limb. It would also be prudent to ensure that the unused ACF be stored in an airtight container to prevent deterioration of the charcoal prior to required use, once opened from its sealed packaging.

Before inserting the ACF, it is essential that the equipment is flushed with oxygen at 10 lpm for at least 90 seconds, the vapouriser is removed from the workstation and replacement of an uncontaminated breathing circuit and soda lime canister is undertaken. This markedly shortens the preparation time, and potentially saves hundreds of dollars in theatre time.

With this cost reduction, the use of filters is more financially viable. The use of charcoal filters may also introduce a method of standardising our approach to preparing an anaesthetic workstation for patients who are MH-susceptible.

Our study is limited in that it did not test all configurations of filters, flushing, circuit changes and flow rates. These limitations relate to the expense

of hiring the Miran gas analyser and the time taken to prepare and carry out each experiment. We limited our experiments to those we considered clinically relevant in preparing an anaesthetic workstation for an MH-susceptible patient and where we thought that previous studies and published information would benefit from clarification. We acknowledge that what is technically possible with ACFs may not translate to best clinical practice in every institution.

The answers to the three questions:

1. Do we need to change the filters every hour? No—not in routine preparation of a machine for an elective MH patient.
2. Do we need to flush the circuit prior to filter installation? Yes.
3. Do we need to replace the circuit and soda lime? Yes.

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