

Residual volatile anesthetics after workstation preparation and activated charcoal filtration

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Background: Volatile anesthetics potentially trigger malignant hyperthermia crises in susceptible patients. We therefore aimed to identify preparation procedures for the Draeger Primus that minimize residual concentrations of desflurane and sevoflurane with and without activated charcoal filtration.

Methods: A Draeger Primus test workstation was primed with 7% desflurane or 2.5% sevoflurane for 2 hours. Residual anesthetic concentrations were evaluated with five preparation procedures, three fresh gas flow rates, and three distinct applications of activated charcoal filters. Finally, non-exchangeable and autoclaved parts of the workstation were tested for residual emission of volatile anesthetics. Concentrations were measured by multicapillary column-ion mobility spectrometry with limits of detection/quantification being <1 part per billion (ppb) for desflurane and <2.5 ppb for sevoflurane.

Results: The best preparation procedure included a flushing period of 10 minutes between removal and replacement of all parts of the ventilator circuit which immediately produced residual concentrations <5 ppm. A fresh gas flow of 10 L/minute reduced residual concentration as effectively as 18 L/minute, whereas flows of 1 or 5 L/minute slowed washout. Use of activated charcoal filters immediately reduced and maintained residual concentrations <5 ppm for up to 24 hours irrespective of previous workstation preparation. The fresh gas hose, circle system, and ventilator diaphragm emitted traces of volatile anesthetics.

Conclusion: In elective cases, presumably safe concentrations can be obtained by a 10-minute flush at ≥ 10 L/minute between removal and replacement all components of the airway circuit. For emergencies, we recommend using an activated charcoal filter.

1 | INTRODUCTION

Malignant hyperthermia is rare and susceptible patients need specific anesthetic management.¹ Volatile anesthetics are well-known triggering agents, so exposure should be avoided.^{2,3} Anesthesia workstations regularly used with volatile anesthetics can emit

potentially triggering residual concentrations of volatile anesthetics. The Malignant Hyperthermia Association of the United States (MHAUS)⁴ and the European Malignant Hyperthermia Group (EMHG)⁵ recommend three possible options to use anesthesia workstations to provide “trigger-free” anesthesia. The first option is to use a “vapor-free” workstation—a workstation that has never been

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exposed to volatile anesthetics. The second option is the preparation of a workstation by the replacement of exchangeable parts of the breathing circuit and flushing. And the third option is to use activated charcoal filters.

Given the cost of modern anesthesia workstations and the rarity of malignant hyperthermia, it is usually impractical to reserve a dedicated “vapor-free” workstation. Thus, workstation preparation and flushing are often performed. A most probably safe threshold of 5 parts per million (ppm) was established based on expert opinions and a single study performed in swine.⁶ So previous studies assessing the preparation of the Draeger Primus reported their results down to 5 ppm.⁷⁻⁹ We use the far more accurate technique of multicapillary column-ion mobility spectrometry (MCC-IMS) which detects volatile anesthetics down to concentrations of several parts per billion (ppb),¹⁰ thereby allowing us to reliably distinguish residual anesthetic concentrations after various preparation methods and identify the best.

We also evaluated activated charcoal filters.¹¹ There is compelling evidence that these filters effectively absorb volatile anesthetics.^{11,12} However, published studies did not evaluate positioning a single filter close to the patient without a replacement of the breathing circuit which might save time in emergency situations.

At least non-exchangeable and non-disposable components of the anesthesia workstation are apparently major sources of residual concentrations. Inert coating of the inner surface of a fresh gas hose may reduce, but not totally exclude, absorbance and emission of volatile anesthetics. Furthermore, it is unclear, whether autoclaving completely eliminates the emission of residual concentrations.

We therefore investigated the effectiveness of Draeger Primus machine component replacement, various fresh gas flows, and different applications of activated charcoal filters on residual concentrations of desflurane and sevoflurane, and finally investigated the emission of residual concentrations by non-exchangeable and autoclaved parts.

2 | MATERIAL AND METHODS

An anesthesia workstation (Primus, Draeger) was used with matching accessories (breathing tubes: Draeger Anesthesia set VentStar[®],

Editorial Comment

This investigation presents a detailed description for how one can minimize residual concentrations of desflurane and sevoflurane to a safe level if the anesthesia workstation must be made rapidly ready for a malignant hyperthermia-susceptible patient. The simplest and quickest method is to place an activated charcoal filter at the Y-piece.

disposable, basic, 2 L, 1.8 m/1.5 m, latex-free; carbon dioxide absorber: Draeger CLIC Absorber 800+; test lung: Draeger SelfTestLung™; sample tube and water trap of the capnography: Draeger Waterlock[®] 2 and sample tube; heat and moisture exchanger: Gibeck Humid-Vent[®]). The workstation was primed by ventilating a test lung with desflurane (7%) or sevoflurane (2.5%) for two hours at a fresh gas flow of 1 L/minute (100% oxygen). Ventilatory parameters were as follows: tidal volume = 500 mL, ventilation frequency = 12/minute, PEEP 5 mbar.

Gas sampling was started within a maximum of 30 seconds after preparation from the inspiratory limb of the workstation and repeated at 5-minute intervals (sampling position 1, Figure 1). The concentrations of desflurane and sevoflurane were measured by multicapillary column-ion mobility spectrometry (MCC-IMS by B&S Analytik, Dortmund, Germany). Visual Now 3.6 (B&S Analytik) software was used to quantify peak intensity in volts. Defined standards of desflurane and sevoflurane ranging from 1 to 7000 ppb (0.001 to 7 ppm) were used for calibration. Limits of detection and limits of quantification were determined as previously described by Maurer et al.¹³ Limit of detection/quantification was 0.8/0.9 ppb (0.0008/0.0009 ppm) for desflurane, and 2.2/2.4 ppb (0.0022/0.0024 ppm) for sevoflurane.

2.1 | Assessment of different preparation procedures and fresh gas flow rates

After priming, the vaporizer was removed, and the fresh gas flow was set to 18 L/minute until the detection limit of the internal optical

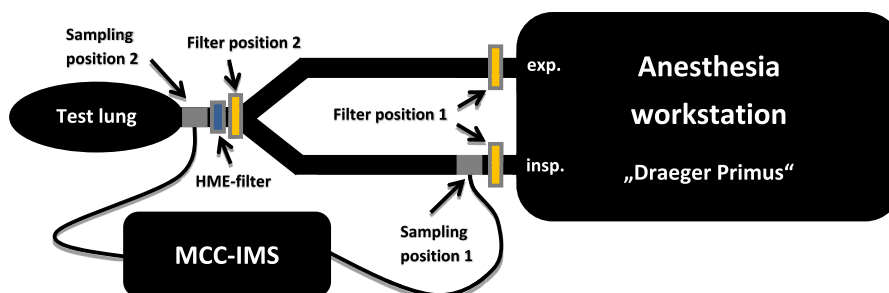


FIGURE 1 Experimental setup during measurement period. Residual concentrations were measured at sampling position 1 to evaluate different preparation procedures, different rates of fresh gas flow and activated charcoal filters at filter position 1. Sampling position 2 was only used for the assessment of one activated charcoal filter at the y-piece (filter position 2). exp./insp., expiratory/inspiratory limb of the circle system; HME, heat and moisture exchanger; MCC-IMS, multicapillary column-ion mobility spectrometer [Colour figure can be viewed at wileyonlinelibrary.com]

sensors was reached (approximately 90 seconds). The respective preparation procedure was subsequently performed (Table 1). After each preparation procedure, a compliance and leak test was carried out. The sample tube of the MCC-IMS was connected to the inspiratory limb by a t-piece and measurements were started (sampling position 1, Figure 1). During the measurement period, fresh gas flow was set to 18 L/minute and a new test lung was ventilated with the same ventilatory settings used for priming. Each preparation procedure was tested three times for 1000 minutes. Finally, the best preparation procedure was evaluated once with each fresh gas flow of 1, 5, and 10 L/minute. Experimental setup, priming, and preparation remained the same.

2.2 | Assessment of activated charcoal filters

Priming of the workstation was done as already described above. A fresh gas flow of 10 L/minute, a new heat and moisture exchanger and a new test lung was used during the measurement period. Three different filter applications (Vapor-Clean, Dynasthetics) were assessed, each with desflurane and sevoflurane.

1. The best tested preparation was combined with the additional placement of activated charcoal filters at the inspiratory and expiratory limb of the circle system (filter position 1, sampling position 1, Figure 1).
2. Filter application was performed according to the manufacturer's recommendations, which includes replacement of the breathing tubes, breathing bag and the placement of activated charcoal filters at the inspiratory and expiratory limb of the circle system (filter position 1, sampling position 1, Figure 1).
3. Only one filter was placed at the y-piece of the breathing tubes without other changes to the breathing circuit than the heat and moisture filter. The t-piece for sampling was therefore moved from the inspiratory limb of the circle system to the test lung (filter position 2, sampling position 2, Figure 1).

TABLE 1 Definition of preparation procedures

Procedure	Exchanged parts of the ventilator circuit
1	None
2	Breathing tubes/bag, carbon dioxide absorber
3	Breathing tubes/bag, carbon dioxide absorber, circle system, ventilator diaphragm
4	Breathing tubes/bag, carbon dioxide absorber, circle system, ventilator diaphragm, sample tube, and water trap of the capnography
5	Additional 10-minute flush between removal and replacement of the same parts as in procedure 4

Note: Circle system and ventilator diaphragm were replaced by autoclaved parts. All other parts were replaced by new parts. Humid and moisture exchanger was changed in all procedures. With each procedure, a new non-contaminated test lung was ventilated during the measurement period.

Compliance and leak test was omitted during the second and third method, as these approaches were designed for emergency use when time is limited.

2.3 | Assessment of trace concentrations emitted by different parts of the workstation

Our local technician provided a used fresh gas hose removed during inspection of a Draeger Primus. The inner diameter was 6 mm with a length of 70 cm resulting in a volume of approximately 20 mL and a surface area of 130 cm². The circle system and ventilator diaphragm were cleaned according to the local hygiene protocol (1-hour thermodesinfector, minimum exposure time to 93.7°C of 5 minutes; autoclaving at 134°C). Fresh gas hose and ventilator diaphragm were placed in a perfluoroalkoxy alkane container (2.7 L) at 20°C. The container was flushed with purified air (ALPHAGAZ™ 1 LUFT, Air Liquide) for two minutes and repeated headspace samples were subsequently taken by MCC-IMS over one hour. The circle system was investigated by taking samples from the inspiratory limb placed in a climatized room at 20°C over one hour. The highest measured concentration was taken as the emitted concentration.

2.4 | Statistics

Statistics were calculated with SigmaPlot 12.5 (Systat Software GmbH). Data are presented as means ± SDs. After testing for normality by Shapiro-Wilk test, comparisons were performed by a one-way ANOVA followed by multiple comparisons with Bonferroni correction. $P < .05$ was considered as statistically significant. Washout curves were fitted by nonlinear regression to appropriate mathematical functions.

3 | RESULTS

Initial tests before finalization of the study design showed that ventilation of a test lung is critical to allow a sufficient washout. Therefore, washout was investigated under standardized ventilation of a test lung. Washout was best described by an exponential decay function with three variables: $[\text{Concentration}] = y_0 + a * e^{-b[\text{Time}]}$.

3.1 | Assessment of different preparation procedures and fresh gas flow rates

Washout times were faster when the circle system and ventilator diaphragm were replaced (Table 2). Further analyzes were therefore restricted to procedures 3-5 to identify the best (Table 3). Procedure 5 showed the lowest residual concentrations, especially during early washout times (Figure 2). The influence of the fresh gas flow rate after performing the best tested preparation (procedure 5) is shown

in Table 3. A prolonged washout was observed for both volatile anesthetics when lower fresh gas flows were used (Figure 3). Even after 1000 minutes, some residual volatile anesthetic remained.

3.2 | Assessment of activated charcoal filters

All applications of activated charcoal filters reduced and maintained residual concentrations of volatile anesthetics <5 ppm (= 5000 ppb) for 24 hours immediately after filter placement (within a maximum of 30 seconds after placement). No volatile anesthetic was detectable for 24 hours when preparation procedure 5 was combined with activated charcoal filters at the inspiratory and expiratory limb of the workstation. Carrying out manufacturer's recommendations, desflurane concentrations ranged from 0.9 to 2 ppb (0.0009 to 0.002 ppm) and sevoflurane concentrations were below the limit of detection (<2.2 ppb, 0.0022 ppm) for 24 hours. Even a single filter at the y-piece of the breathing tubes with no other changes than the heat and

moisture filter reduced desflurane concentrations to a range from 1 to 1.8 ppb (0.001 to 0.0018 ppm), and sevoflurane concentrations to a range from 2.2 to 5.6 ppb (0.0022 to 0.0056 ppm) for 24 hours.

3.3 | Assessment of trace concentrations emitted by different parts of the workstation

The fresh gas hose emitted residual concentrations of 1 ppb (0.001 ppm) desflurane and 6.7 ppb (0.0067 ppm) sevoflurane. The ventilator diaphragm emitted 0.9 ppb (0.0009 ppm) desflurane and 5.1 ppb (0.0051 ppm) sevoflurane. Residual concentrations in the inspiratory limb of the circle system were 0.9 ppb (0.0009 ppm) of desflurane and below the limit of quantification for sevoflurane.

4 | DISCUSSION

4.1 | Assessment of different preparation procedures and fresh gas flow rates

All preparation procedures that included a change of circle system and ventilator diaphragm resulted in residual concentrations <5 ppm for either anesthetic immediately after preparation (within a maximum of 30 seconds after preparation). Washout was faster with an additional 10-minute flushing period between removal and reassembly of all exchangeable parts of the ventilator circuit. Our results are consistent with Crawford et al who also showed that replacing circle system and ventilator diaphragm markedly reduced residual concentrations.⁸

Prinzhausen et al reported much longer mean washout times for sevoflurane, needing 65 minutes to reach concentrations <5 ppm.⁹

TABLE 2 Washout times to reach concentrations <5 ppm (5000 ppb)

Procedure	Time to [desflurane] <5 ppm in min	Time to [sevoflurane] <5 ppm in min
1	115 ± 30 (95-150)	107 ± 20 (85-125)
2	103 ± 19 (90-125)	110 ± 20 (90-130)
3	3 ± 3 (0-5)	3 ± 3 (0-5)
4	3 ± 3 (0-5)	3 ± 3 (0-5)
5	0 ± 0 (0)	0 ± 0 (0)

Note: Data presented as means ± SDs (minimum-maximum). Each procedure was performed three times.

	Desflurane			Sevoflurane		
<i>Comparison of preparation procedures</i>						
Flow [L/min]	18					
Procedure	3	4	5	3	4	5
10 min	383 ± 41*	320 ± 42*	215 ± 32	366 ± 141	374 ± 134	268 ± 63
100 min	214 ± 92	244 ± 30*	70 ± 6	112 ± 32	108 ± 24	75 ± 42
1000 min	28 ± 11*	22 ± 6	6 ± 2	8 ± 2	9 ± 2	7 ± 1
<i>Comparison of different fresh gas flow rates</i>						
Procedure	5					
Flow [L/min]	1	5	10	1	5	10
10 min	2661	916	141	6707	1658	204
100 min	2297	345	72	5653	145	89
1000 min	72	41	13	3	5	5

Note: The upper part of the table compares different preparation procedures. Procedure 5 was identified to lead to the lowest residual concentrations of both volatile anesthetics. The lower part of the table shows the influence of different fresh gas flow rates on washout after performing procedure 5. *P < .05 vs procedure 5, one-way ANOVA, multiple comparisons Bonferroni corrected. Data presented as means ± SDs. Values are given in ppb (1 ppb = 0.001 ppm).

TABLE 3 Residual concentrations of desflurane and sevoflurane 10, 100 and 1000 min after preparation of the workstation (Draeger Primus)

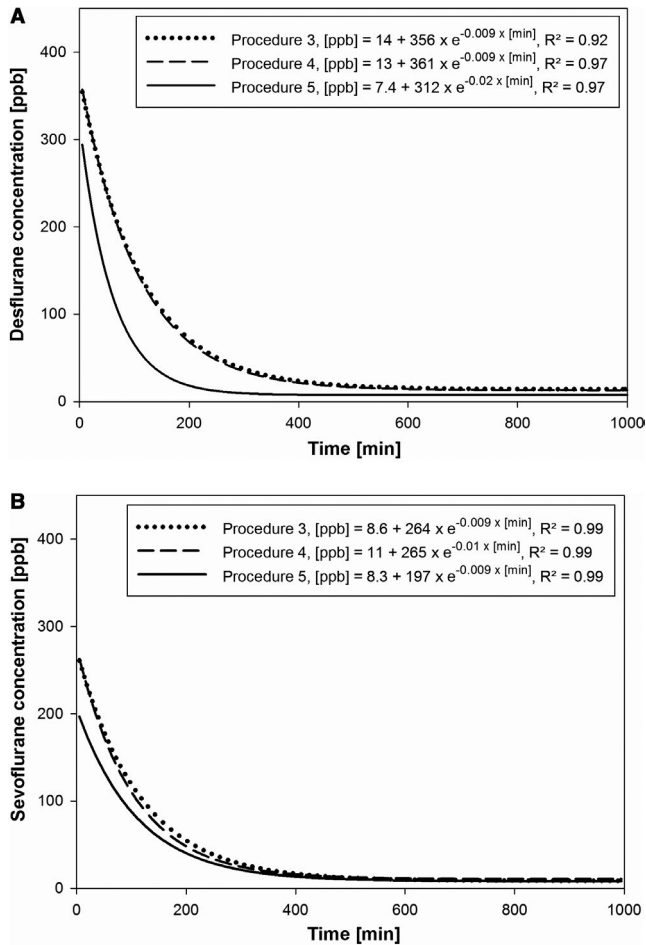


FIGURE 2 A and B, Washout curves for desflurane (top, A) and sevoflurane (bottom, B) following preparation procedures 3-5 (1 ppb = 0.001 ppm). Procedure 3: exchange of breathing tubes/bag, carbon dioxide absorber, circle system, ventilator diaphragm; procedure 4: exchange of breathing tubes/bag, carbon dioxide absorber, circle system, ventilator diaphragm, sample tube and water trap of the capnography; procedure 5: additional 10-min flush between removal and replacement of the same parts as in procedure 4. Nonlinear regression was performed using the mean values of the three measurement runs of each procedure. The coefficient of determination (R^2) describes the fit of the mean values and the respective regression model

The key distinction appears to be that Prinzhausen et al did not perform an exchange of the ventilators diaphragm during preparation. Cottron et al also report long washout times for sevoflurane at a median of 42 minutes to reach concentrations below 5 ppm.⁷ Fresh gas flow was identical with our approach at 18 L/minute, but the ventilators diaphragm was apparently unchanged. Available data therefore suggests that replacing all exchangeable parts of the ventilator circuit is critical to speed washout. Our results further show that additional 10 minutes of flushing between part removal and reassembly further reduces residual volatile anesthetic concentrations.

Washout after the best preparation was considerably faster with a fresh gas flow of 10 L/minute than with 1 or 5 L/minute,

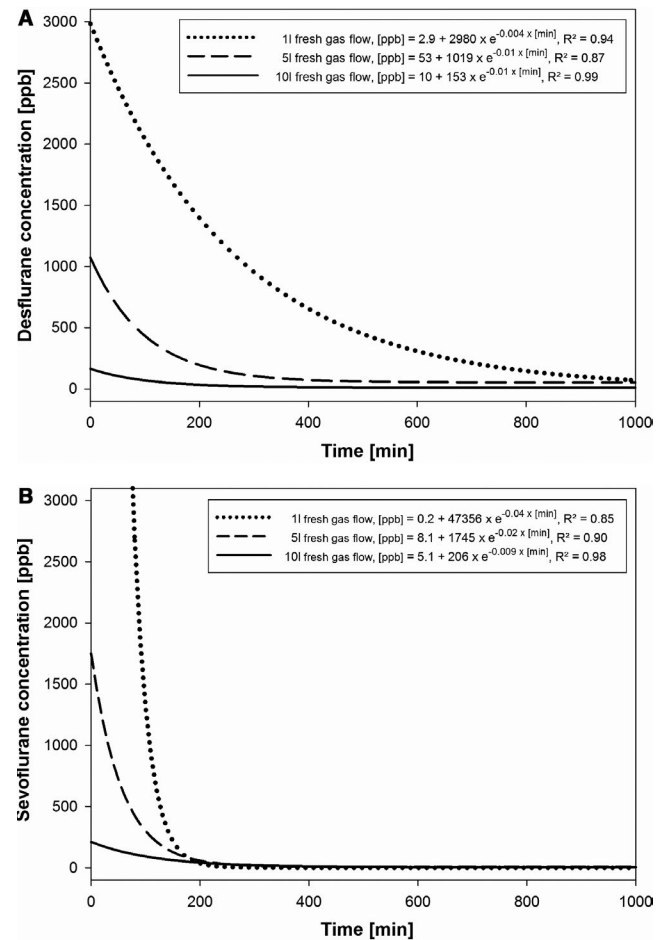


FIGURE 3 A and B, Washout curves for desflurane (top, A) and sevoflurane (bottom, B) following the best tested preparation procedure (5) with 1, 5, and 10 L/min fresh gas flow (1 ppb = 0.001 ppm). Each fresh gas flow rate was tested once. Procedure 5: 10-min flush between removal and replacement of breathing tubes/bag, carbon dioxide absorber, circle system, ventilator diaphragm, sample tube, and water trap of the capnography. Nonlinear regression was performed to obtain washout curves. The coefficient of determination (R^2) describes the fit of the measurement values and the respective regression model

but increasing flow to 18 L/minute did not further speed washout. We thus recommend using a fresh gas flow of 10 L/minute after preparing the machine. An alternative strategy is to use a high gas flow such as 10 L/minute until presumably safe concentrations are reached, and then continue with a lower flow. However, previous studies detected a significant rebound in the concentration after changing to low flow rates.^{8,9} A fresh gas flow of 10 L/minute should thus be used for washout, and then maintained during anesthesia.

4.2 | Assessment of activated charcoal filters

Activated charcoal filters immediately reduced residual volatile anesthetic concentrations below 5 ppm (within a maximum of

30 seconds) and remained them below 5 ppm for 24 hours. Volatile anesthetics were no longer detectable, even at parts-per-billion concentrations when optimal workstation preparation was combined with two activated charcoal filters. Our results are generally consistent Neira et al who showed that the combination of Draeger Zeus workstation preparation and charcoal filters was more effective than workstation preparation alone.¹⁴ The first study that used FDA-approved activated charcoal filters reported an immediate reduction of volatile anesthetics within 2 minutes and concentrations remaining below 5 ppm for 60 minutes.¹¹ Further studies showed the reduction of residual concentrations below 5 ppm by filter placement over 12¹² and even up to 24 hours.¹⁵ We extend previous results by showing that the application of a single activated charcoal filter at the Y-piece was as effective as the recommended use which includes replacement of breathing tubes and bag and the placement of two filters at inspiratory and expiratory limb of the circle system. Taken altogether, every use of activated charcoal filters that we assessed maintained residual concentrations below 5 ppm for at least 24 hours. Positioning a single filter at the y-piece appears to be perfectly effective—and is both fast and inexpensive.

4.3 | Assessment of trace concentrations emitted by different parts of the workstation

Optimal preparation and flushing massively reduced emission of anesthetics, but residual concentrations remained detectable even after 16 hours of flushing. The reason appears to be that non-exchangeable and autoclaved components continue to release trace concentrations of volatile anesthetics. The fresh gas hose emitted the highest concentrations, presumably due to its strong exposure to volatile anesthetics, as it connects vaporizers to the circle system. While autoclaving helped, it did not fully eliminate trace concentrations. Both, circle system and ventilator diaphragm emitted desflurane and sevoflurane. It seems unlikely that parts-per-billion residual anesthetic concentrations trigger malignant hyperthermia. But to totally avoid exposure to volatile anesthetics, use of activated charcoal filters or a never-exposed “vapor-free” workstation is necessary.

5 | CONCLUSION

Optimal preparation of a Draeger Primus workstation for patients susceptible to malignant hyperthermia differs—with the replacement of workstation components for elective and the use of activated charcoal filters for emergency cases. The best preparation procedure includes a 10-minute flush ≥ 10 L/minute between removal and reassembly of all parts of the ventilator circuit. In case of emergencies, when malignant hyperthermia is suspected or urgent anesthesia for susceptible patients is indicated, we recommend using an activated charcoal filter. The first option (intended

use) includes the replacement of breathing tubes and bag, and insertion of two activated charcoal filters on the inspiratory and expiratory limbs. Alternatively, the placement of a single activated charcoal filter at the y-piece is fast, inexpensive, and equally effective—but an off-label use. Workstation preparation or filter use should be followed by a fresh gas flow of 10 L/minute during the subsequent procedure. Finally, the very lowest concentrations will be obtained when machine preparation and activated charcoal filters are combined, or by using a workstation never exposed to volatile anesthetics.

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CONFLICT OF INTEREST

The authors have no conflicts of interest.

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