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Surgical smoke: still an underestimated health hazard in the operating theatre

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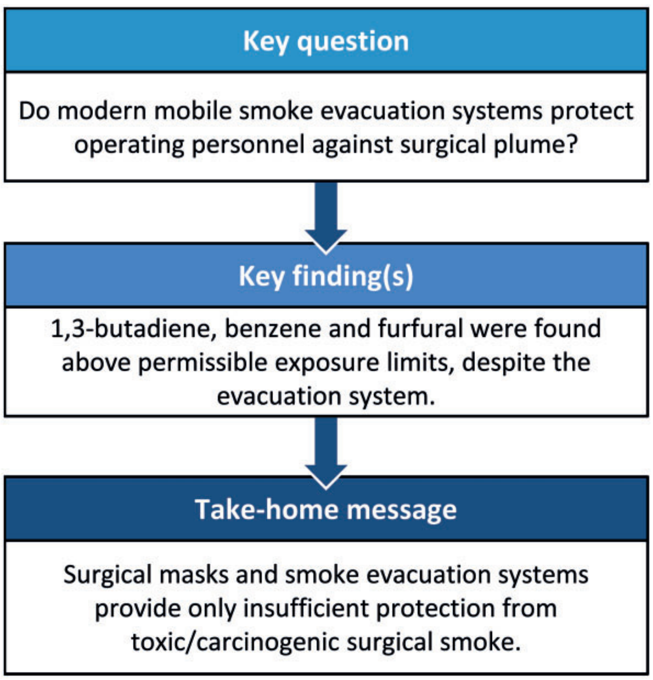

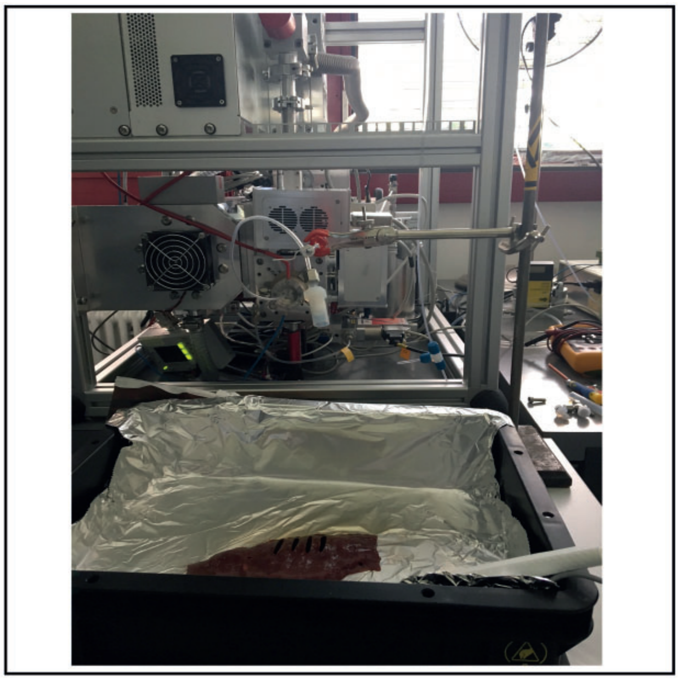

Abstract

OBJECTIVES: Smoke generated from electrocautery dissection contains irritating and/or carcinogenic components. The aim of this study was to investigate the effectiveness of a mobile smoke evacuation system (SES) in protecting surgical personnel from these hazardous fumes.

METHODS: Standardized cuts with an electrocautery device were performed on fresh porcine tissue, and the generated surgical fume was analysed with and without the additional use of a mobile SES using a real-time proton-transfer-reaction time-of-flight mass spectrometer. Furthermore, 2 different surgical masks were tested to investigate their filter capacity.

RESULTS: Several toxic and/or carcinogenic volatile organic compounds including 1,3-butadiene, benzene and furfural were found in concentrations clearly above the limits that were set by the National Institute of Occupational Safety and Health: 1,3-butadiene at 19.06 ± 1.54 ppb (limit: 5 ppb), benzene at 6.21 ± 1.33 ppb (limit: 0.5 ppb) and furfural at 14.34 ± 2.97 ppb (limit: 2 ppb). Although the mobile SES was able to reduce these substances to a certain degree, butadiene and benzene still remained above the permissible exposure

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limits with concentrations of 14.21 ± 0.07 and 1.16 ± 0.05, respectively. Both surgical masks were unable to reduce the 'inhaled' concentrations of volatile organic compounds.

CONCLUSIONS: Although the SES reduced the concentrations of most of the detected volatile organic compounds to a certain amount, especially the carcinogenic substances, butadiene and benzene remained high above exposure limits. According to the abovementioned significant data, further investigation on this topic is imperative, especially when considering that surgical masks were absolutely ineffective in protecting individuals from the toxic smoke and that the cautery was only used for 10 s in this experiment.

Keywords: Smoke • Plume • Electrocautery • Benzene • Furfural • Mass spectrometer

INTRODUCTION

The use of electrocautery during surgery results in the dispersion of fine particles and the creation of a plume. This surgical plume is as mutagenic as cigarette smoke. It has been demonstrated that the mutagenic potency resulting from the pyrolysis of 1 g of tissue is equivalent to smoking 6 unfiltered cigarettes [1]. It is also known that surgical plume contains a variety of hazardous compounds such as acrolein, benzene, carbon monoxide, formaldehyde, hydrogen cyanide, methane, toluene and polycyclic aromatic hydrocarbons. Most of these substances are also found in cigarette smoke. All these chemicals are either known to be carcinogenic (polycyclic aromatic hydrocarbon and benzene), mutagenic (formaldehyde and toluene) or at least respiratory irritants (acrolein, carbon monoxide, formaldehyde, hydrogen cyanide and methane), which makes them all hazardous to the individuals who work in the environment of an operating room (OR). In addition, viruses, bacteria and viable cells may be released during electrocautery of tissue and carried around in the air by the plume until they are eventually inhaled by the OR personnel [2–8]. To reduce those potential hazards, simple protective measures for the OR personnel such as surgical masks and room ventilation systems have become standard practice. In addition, in many countries in Europe as well as in the USA the relevant national institutes for occupational safety and health strongly advise the use of mobile or portable smoke evacuation systems (SESs) because general room ventilation has been found to be inefficient in sufficiently clearing surgical plume from the OR. Nevertheless, the crucial question remains as to whether these additional measures are appropriate to make surgical smoke inoffensive for OR personnel. Our hypothesis was that carcinogenic compounds could be found in the OR air above permissible exposure limits when not using an additional SES but that guidelines on exposure limits would be met when using an SES at full suction power.

The present study is the first one to investigate the effectiveness of a mobile SES, presenting a detailed real-time analysis of surgical smoke compound concentrations using a state-of-the-art proton-transfer-reaction mass spectrometer (PTR-MS). Furthermore, the effectiveness of 2 different surgical masks in protecting personnel from smoke exposure is investigated.

MATERIALS AND METHODS

Experimental setup

As porcine tissue is the most physiologically similar to human tissue [9], electrosurgical smoke was produced by the application of electrocoagulation on a porcine animal tissue in an open surgery model. Tissue specimens were purchased fresh from the local butcher on the day of the experiments and were at room temperature (24°C) when the experiments were started. The meat was placed on a sheet of tin foil, with the neutral electrode being positioned on the tin foil under the specimen. A standard monopolar cautery device (VIO 300D, ERBE Swiss AG, Winterthur, Switzerland) was applied to 2 different types of tissue: fresh porcine liver and fresh porcine muscle tissue (from the pig's neck). The electrocautery settings that were used for the experiment were set at 'Spray coagulation', effect 2 at a constant power of 80 W. These settings are the ones that are most commonly used in the OR of our thoracic surgical unit when performing, for example, a thoracotomy. Furthermore, 3 other common electrocautery settings were tested as well to find out whether the electrocautery setting itself has an influence on the concentration of the measured volatile organic compounds (VOCs): Autocut (effect 4, 100 W), High cut (effect 4, 180 W) and Swift cut/coagulation (effect 4, 100 W). While the 'Autocut' mode is the standard setting for cutting, for example, human skin, 'High cut' is more powerful and can be applied in case of dense scar tissue. Finally, the 'Swift cut/coag' mode is a mix between cutting and coagulation because it cuts quite well through tissue, although there is slightly less coagulation as compared to 'Spray coag'.

Cuts of a defined length of 3 cm were performed during a defined period of time of 10 s. In between the cuttings, a break of 2–3 min was made until the MS showed that air concentrations of VOCs were back to normal levels (as measured before the beginning of the experiments). For both pieces of meat, a series of 3 cuttings was performed first with and then without the additional use of a latest-generation mobile SES (IES 2, ERBE Swiss AG, Winterthur, Switzerland).

Smoke samples were analysed in the environment of a closed lab room with standard ventilation, but it has to be noted that no vertical laminar flow was installed. The inlet of the PTR-MS had a diameter of 0.5 cm for smoke collection and was placed 20 cm above the meat pieces. Through this inlet, the air samples were directly and continuously transferred via a suction catheter to the MS, which was situated 50 cm beside the station where the sample tissue was cut.

Besides the abovementioned basic test, we also investigated the filter capacity of 2 different surgical masks: (i) standard surgical mask: Lite One® (Kimberly-Clark, Roswell, USA) and (ii) 3M™ VFLEX™/mask 2 (3M AG, Rüschlikon, Switzerland). For these tests, the corresponding mask was tightly fitted over the inlet of the PTR-MS, and the same standard cuts were made as described earlier.

Finally, the exhaust gases, which are expelled at the bottom of the mobile SES and expelled back into the OR, were also examined by the PTR-MS. For this experiment, the liver tissue was cut during a time of 20 s (cut length 6 cm), and the SES was operated at a suction power of 100%. The exhaust gases of the SES that are expelled at the bottom of the machine were again examined using the PTR-MS by moving the instrument inlet from the cutter side to the exhaust side of the suction device.

Proton-transfer-reaction mass spectrometer

Smoke analysis was performed using a PTR-MS (Vocus PTR-TOF, TOFWERK AG, Thun, Switzerland), allowing for the detection, identification and quantification of ionized molecules in real time (Fig. 1). Its functional principle has been described previously [10]. The dimensions of the PTR-MS are 80 × 40 × 56.5 cm. The applied settings were fixed as follows: drift, 400 V; pressure, 1 mBar.

The reaction conditions were set using a uniform drift field of 400 V across the reactor length (10 cm) and a pressure of 1 mbar. PTR-MS is particularly well suited for the study of vapours arising from the use of surgical cutting processes because it is a soft ionization approach, which is capable of ionizing a wide range of VOCs in a controlled and quantitative manner with very high sensitivity (<100 parts per quadrillion) in real time.

Figure 1: Real-time proton transfer reaction time-of-flight mass spectrometer.

Data analysis

Data were analysed using Tofware, a TOF data analysis software package (TOFWERK AG, Thun, Switzerland). Data are reported as mean ± standard deviation for each experiment (i.e. 1 incision). The mass calibration of the spectra was done with internal water clusters and benzene, toluene and xylene peaks. The independently verified mass accuracy using other known peaks in the spectrum (i.e. acetone) was verified to be <3 ppm, allowing molecular compositions to be assigned from the mass spectra. The resolving power of the instrument was $R_{FWHM} = 5000$, allowing reliable separation of isobars in the region of the mass spectrum of interest. When possible the measured isotopic distribution was used as an additional constraint to help confirm molecular assignment in addition to the mass accuracy of the instrument.

Smoke evacuation system

For smoke evacuation, a mobile SES (IES 2, ERBE Swiss AG, Winterthur, Switzerland) was used. The SES consists of a special hand piece with an integrated aspirator near the electrocautery tip (Fig. 2A). From the hand piece, there is a standard electrical plug and an additional aspirator connector, which then leads to the smoke evacuator machine (Fig. 2B). As the SES is fully compatible with standard cautery systems that are received from ERBE, the smoke evacuator is automatically activated as soon as the cautery is used. The IES 2 has a suction output of >550 l/min and has an integrated ULPA filter (ultra-low penetration air filter that efficiently removes 99.9999% of particles with a size of 0.12 μm and larger) combined with an active carbon filter. The

Figure 2: (**A**) Hand piece with an integrated aspirator and (**B**) a smoke evacuator.

Table 1: Influence of the SES on the concentration of VOCs

	Liver No SES	Liver SES 60%	Liver SES 100%	Muscle No SES	Muscle SES 60%	Muscle SES 100%	PEL (ppb)
1,3-Butadiene (C_4H_6) (ppb)	19.06 ± 1.54	15.57 ± 0.63	14.21 ± 0.07	15.40 ± 0.65	13.17 ± 0.02	13.25 ± 0.04	5
Benzene (C_6H_6) (ppb)	6.21 ± 1.33	2.59 ± 0.49	1.16 ± 0.05	2.45 ± 0.37	1.33 ± 0.04	1.09 ± 0.02	0.5
Furfural ($C_5H_4O_2$) (ppb)	14.34 ± 2.97	5.29 ± 1.13	0.99 ± 0.11	0.49 ± 0.07	0.21 ± 0.02	0.18 ± 0.00	2

Values are presented as mean ±1 SD.
PEL: permissible exposure limit; SD, standard deviation; SES: smoke evacuation system; VOC's: volatile organic compounds.

Table 2: Influence of the surgical mask on the concentration of VOCs

	Liver No SES	Liver No SES Mask 1	Liver No SES Mask 2	Muscle No SES	Muscle No SES Mask 1	Muscle No SES Mask 2	PEL (ppb)
1,3-Butadiene (C_4H_6) (ppb)	19.06 ± 1.54	21.62 ± 1.13	19.06 ± 0.88	15.40 ± 0.65	18.65 ± 1.02	23.05 ± 2.25	5
Benzene (C_6H_6) (ppb)	6.21 ± 1.33	6.77 ± 0.70	5.82 ± 0.59	2.45 ± 0.37	4.05 ± 0.47	6.14 ± 0.77	0.5
Furfural ($C_5H_4O_2$) (ppb)	14.34 ± 2.97	7.84 ± 0.66	11.27 ± 1.13	0.49 ± 0.07	0.50 ± 0.02	0.72 ± 0.05	2

Values are presented as mean ±1 SD.
PEL: permissible exposure limit; SD, standard deviation; SES: smoke evacuation system; VOC's: volatile organic compounds.

suction output can be adjusted continuously, whereas the standard setting is 60% of suction power. According to the manufacturer, the standard setting of 60% was chosen because the SES does emit a slightly louder suction noise if the suction power is increased to 80% or even 100%. For our experiments, we used both the standard setting as well as 100% suction power to evaluate the difference in the efficiency of the device.

RESULTS

In both types of meat, 9 main toxic and/or carcinogenic substances were identified as compounds of the surgical smoke: acetylene (C_2H_2, exact mass: 26.01565 Da); hydrogen cyanide (HCN, exact mass: 27.01090 Da); 1,3-butadiene (C_4H_6, exact mass: 54.04695 Da); benzene (C_6H_6, exact mass: 78.04695 Da); toluene (C_7H_8, exact mass: 92.06260 Da); furfural ($C_5H_4O_2$, exact mass: 96.02113 Da); styrene (C_8H_8, exact mass: 104.06260 Da); ethyl benzene (C_8H_{10}, exact mass: 106.07825 Da) and 1-decene ($C_{10}H_{20}$, exact mass: 140.15650 Da). The identification of these compounds was confirmed using 2 independent constraints: the instrument mass accuracy and the comparison of the experimental isotopic distribution with the theoretical ratio. Especially in the mass range of these molecules, these 2 constraints provide robust ion identification. All peaks were detected as protonated parent peaks.

Influence of the smoke evacuation system on the concentration of volatile organic compounds

The results of these measurements are listed in Table 1. Furthermore, we included the permissible exposure limits as defined by the Swiss National Institute for Occupational Safety and Health (SUVA) in our table. Although we used the cautery only for 10 s in our tests, butadiene, benzene and furfural clearly exceeded these permissible levels. Furthermore, it seems that the cauterization of liver tissue resulted in higher concentrations of butadiene, benzene and, especially, furfural, when compared to muscle tissue. In addition, the SES seems to be less effective when only the standard setting (suction power 60%) is used, compared to 100% suction output, which is not too surprising.

Influence of surgical mask on the concentration of volatile organic compounds

Somewhat more striking was the fact that both masks, especially the 'thicker' 3M model, were not at all able to reduce the inhaled concentration of the 3 main toxic compounds, which are predominantly present in the vapour phase (Table 2).

Influence of electrocautery settings on the concentration of volatile organic compounds

As presented in Table 3, except for slightly higher levels of furfural when 'High cut' was used, the concentrations of our main toxic compounds were more or less the same among the different cutting modes.

Chemical composition of the exhausted air by the smoke evacuation system

As demonstrated in Table 4, the SES device expelled concentrations of our 3 main carcinogenic substances back into the OR that were similar to those measured over the specimen when 10-s cuts were performed on liver tissue with 60% SES suction power (second column of Table 1).

Table 3: Influence of electrocautery settings on the concentration of VOCs[a]

	Muscle Spray Coag 80 W Effect 2	Muscle Autocut 100 W Effect 4	Muscle High cut 180 W Effect 4	Muscle Swift cut/coag 100 W Effect 4	PEL (ppb)
1,3-Butadiene (C_4H_6) (ppb)	15.40 ± 0.65	15.98 ± 1.26	15.73 ± 0.85	14.96 ± 0.54	5
Benzene (C_6H_6) (ppb)	2.45 ± 0.37	3.19 ± 0.76	2.81 ± 0.49	2.19 ± 0.32	0.5
Furfural ($C_5H_4O_2$) (ppb)	0.49 ± 0.07	0.46 ± 0.09	2.62 ± 0.72	0.25 ± 0.03	2

[a]No SES used.

Values are presented as mean ±1 SD.

PEL: permissible exposure limit; SD, standard deviation; SES: smoke evacuation system; VOC's: volatile organic compounds.

Table 4: Chemical compounds in the air exhausted by the SES

Liver tissue	SES at 100%	PEL (ppb)
1,3-Butadiene (C_4H_6) (ppb)	15.88 ± 0.39	5
Benzene (C_6H_6) (ppb)	2.77 ± 0.38	0.5
Furfural ($C_5H_4O_2$) (ppb)	5.55 ± 0.97	2

Cautery activation time: 20 s.

PEL: permissible exposure limit; SES: smoke evacuation system.

DISCUSSION

The use of a PTR-MS enabled us to identify 9 toxic and/or carcinogenic VOCs stemming from the use of a standard electrocautery on porcine tissue. While we measured hundreds of VOCs present in the smoke, we herein report on a subset including acetylene, hydrogen cyanide, 1,3-butadiene, benzene, toluene, furfural, styrene, ethyl benzene and 1-decene, which are consistent with those described in earlier publications [11]. In order to best reproduce the working conditions of the surgeon in the OR, smoke samples were collected at a distance of 20 cm above the cauterized specimens, whereas most of the reported studies so far investigated the surgical plume collected at a distance of 2 cm or less [4].

The use of a highly sensitive proton transfer reaction time-of-flight mass spectrometer allowed a detailed real-time analysis of a suite of VOCs at a high time resolution with sufficient resolving power to extract the molecular composition. PTR-MS analysis does not require sample pretreatment or preparation and operates autonomously. As such, PTR-MS is well suited for monitoring in laboratory environments without distracting from other tasks at hand. In other studies, smoke analysis was carried out by a laser spectrometer or gas chromatography, which lacks the advantage of a real-time analysis and has reduced sensitivity in addition to only a limited spectrum of substances that can be measured with these methods [4, 12].

As demonstrated earlier, the chemical composition of the surgical smoke may vary according to the type of the dissected tissue, i.e. coagulation of epidermal tissue produces higher levels of toluene and ethyl benzene [13, 14]. Conversely, in our experiments the ion intensities of 1,3-butadiene, benzene, furfural, styrene and ethyl benzene did not vary much between the liver and the muscle tissue, except for furfural.

The concentrations of our subset of identified VOCs were found to be several times higher than the allowed occupational exposure limit defined by the Swiss National Institute of Occupational Safety and Health (SUVA).

Although in most countries in Europe and also the USA the corresponding national institutes of health strongly advise the use of mobile SES, these recommendations are only rarely followed. For example, according to data of the NIOSH from 2011 in the USA, only around 15% of surgical units are equipped with mobile SES [15]. In Switzerland, only 30 of more than 300 surgical units have an SES. The reason why SESs are not used as widespread as recommended might be mostly attributable to the fact that the usefulness of mobile SESs has never been investigated and thus proven before. Still, it has to be considered that the standard OR ceiling ventilation eliminates noxious fumes only once they have already passed over the heads of the OR personnel. The common practice of just holding the normal suction device near the cautery tip strongly depends on the person holding the suction, not to forget that the aspirated air is usually not filtered and just expelled back into the OR. Considering that surgical smoke particles smaller than 10 µm are of respirable size, those particles may be inhaled and deposited in the respiratory tract and lungs [16].

In particular, the compounds 1,3-butadiene, benzene and furfural, which are all considered carcinogenic as well as mutagenic, were found at alarmingly high levels despite the additional use of the SES at full power. Nevertheless, mobile SESs are the only available devices so far that are able to clear at least a part of the surgical smoke directly at the source where it is generated and thus especially protect individuals standing directly at the operating table.

This is even more important once one considers that surgical masks are often not fitted tightly and so the surgical plume can be inhaled directly [17]. Even more concerning is the fact that both surgical masks in our experiment, even the thicker model (3M), did not provide any protection from the VOCs in the surgical plume. In fact, we even found that concentrations of the VOCs were even slightly higher with mask 1 compared to the situation without a surgical mask, which we explain by the fact that surgical fumes can get caught and accumulate in a mask that does not fit perfectly (which in the OR is rather common).

Finally, the SES releases gases that remain toxic. Although the latest generation of the SES works with ULPA filters (i.e. an ultra-low penetration air filter that efficiently removes 99.9999% of particles with a size of 0.12 µm and larger), as demonstrated, VOCs still pass these filters and end up in the OR air. In fact, when the cautery was used for 20 s on liver tissue, as much toxic compounds were expelled by the SES back into the OR as were measured directly above the specimen when performing a liver cut of 10 s with 60% SES suction in place. This fact also clearly warrants further developments concerning mobile SES: either the additional integration of better or larger active carbon filters has to be considered and/or the exhaust of the SES must be connected directly to the exhaust of the OR ventilation system.

Although surgical smoke has been shown to be as mutagenic as cigarette smoke [16], scientific evidence on the danger of long-term exposure to surgical smoke is still lacking. Considering the small number of OR personnel and the large number of other contributing environmental factors (including cigarette smoking!), it will most likely be difficult to obtain statistical significance and establish a cause-and-effect relationship between surgical smoke and a possible biological hazard. The cigrette, for example, was found responsible for malignancy of the airways due to the large number of smokers. In the present study, we, therefore, refer to the exposure limits of the National Institute for Occupational Safety and Health, which published these limits based on the knowledge gained from animal toxicity studies and experience with workers who were exposed to the described VOCs.

Limitations

The main limitation of this study is the small number of investigated samples, which was mainly due to the fact that this study was designed as a pilot study, allowing us to test our hypothesis and eventually serve as the basis for a more comprehensive and representative study in our ORs. Furthermore, we only focused on the most toxic substances, even though the proton transfer reaction time-of-flight mass spectrometer allows for the detection of hundreds of compounds simultaneously. The use of either a heated inlet or a different ionization approach would allow the separation of the vapour and particulate phases and would allow further insight into the occupational exposure to toxic substances. All the tests were performed in a 'laboratory setting' and not on living tissue and in an OR with the corresponding ventilation system and vertical laminar flow. The distance between the inlet of the PTR-MS and the specimen was only 20 cm in our tests, which might be a bit more (±30 cm) in 'real OR conditions' depending on the surgeon and the surgical procedure at hand. Furthermore, it has to be stated that we did our measurements in a clearly organized, sequential fashion instead of in a randomized protocol, mainly in order to minimize errors when assigning different settings to different measurements during the analysis of the final results. Nevertheless, as the analysis of the acquired data took several days, we were dealing with a situation that was similar to an observer-blinded setting with the only exception that we could see when the MS was back to normal room air measurements and ready for the next test. As we present only preliminary results, further investigations on VOCs are indispensable to obtain permissible exposure levels for all detectable chemicals in the surgical plume, to encourage employers to undertake risk assessment and finally to establish effective protective measurements.

CONCLUSION

Surgical smoke contains alarmingly high levels of toxic substances and especially a variety of carcinogenic VOCs. Standard protective measures such as surgical masks or the use of an 'on-tip' (connected directly to the cautery tip) mobile SES do not provide the expected protection, even when the SES is operated at full suction power. Furthermore, after the surgical plume is filtered by a prefilter as well as an ULPA filter in the SES, the main identified carcinogenic compounds, 1,3-butadiene, benzene and furfural, were discharged back into the OR at unacceptably high concentrations. Further studies on this topic in the setting of an operating theatre are clearly warranted.

Conflict of interest: none declared.

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