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Surgical smoke control with local exhaust ventilation: Experimental study

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Abstract

This experimental study aimed to evaluate airborne particulates and volatile organic compounds (VOCs) from surgical smoke when a local exhaust ventilation (LEV) system is in place. Surgical smoke was generated from human tissue in an unoccupied operating room using an electrocautery surgical device for 15 min with 3 different test settings: (1) without LEV control; (2) control with a wall irrigation suction unit with an in-line ultra-low penetration air filter; and (3) control with a smoke evacuation system. Flow rate of LEVs was approximately 35 L/min and suction was maintained within 5 cm of electrocautery interaction site. A total of 6 experiments were conducted. Particle number and mass concentrations were measured using direct reading instruments including a condensation particle counter (CPC), a light-scattering laser photometer (DustTrak DRX), a scanning mobility particle sizer (SMPS), an aerodynamic particle sizer (APS), and a viable particle counter. Selected VOCs were collected using evacuated canisters using grab, personal and area sampling techniques. The largest average particle and VOCs concentrations were found in the absence of LEV control followed by LEV controls. Average ratios of LEV

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controls to without LEV control ranged 0.24–0.33 (CPC), 0.28–0.39 (SMPS), 0.14–0.31 (DustTrak DRX), and 0.26–0.55 (APS). Ethanol and isopropyl alcohol were dominant in the canister samples. Acetaldehyde, acetone, acetonitrile, benzene, hexane, styrene, and toluene were detected but at lower concentrations (<500 μg/m^3) and concentrations of the VOCs were much less than the National Institute for Occupational Safety and Health recommended exposure limit values. Utilization of the LEVs for surgical smoke control can significantly reduce but not completely eliminate airborne particles and VOCs.

Keywords

Electrocautery; healthcare workers; local exhaust ventilation; surgical smoke

Introduction

According to the Occupational Safety and Health Administration (OSHA), over 500,000 personnel working in operating rooms (ORs) in the U.S. are potentially exposed to surgical smoke.[1] Exposure to surgical smoke places OR workers at potential risk for negative health effects including pulmonary irritation and inflammation, transmission of infection, and genotoxicity.[2] Animal studies have shown that rats exposed to smoke from pigskin showed congestive pneumonia, bronchiolitis, and emphysema[3] and sheep exposed to smoke from sheep bronchial tissue showed a decrease of arterial PO_2 (hypoxia), depressed tracheal mucus velocity and severe inflammation with dramatic increases of inflammatory cells.[4] In a small number of cases, the development of respiratory diseases was attributed to surgical smoke exposure.[5] Surgical smoke is a mixture of gaseous and particulate by-products from the use of heat-producing (by high-frequency current or laser) surgical devices. Smoke is generated when the devices heat human tissue cells to boiling, resulting in membrane rupture and the dispersal of cellular contents as vapors and fine particles[6] and most of the gas phase component is water or steam from cellular fluid.[7] To date, at least 150 chemicals have been identified in surgical smoke.[8,9] These include acetaldehyde (A3 confirmed animal carcinogen with unknown relevance to humans; American Conference of Governmental Industrial Hygienists (ACGIH)),[10] acrolein, acetonitrile, benzene (A1 confirmed human carcinogen; ACGIH), formaldehyde (A2 suspected human carcinogen; ACGIH), hydrogen cyanide (HCN), polyaromatic hydrocarbons (PAHs), styrene, toluene, and xylene.[2,11–15] There are more than 600 additional chemical compounds that may need to be identified.[16] OR workers can be exposed to high concentrations of particulate matter in the absence of local exhaust ventilation (LEV) control. For instance, particle concentration measured with a laser particle counter increased from 60,000 to over 1 million particles/ft^3 within 5 min of electrocautery use during breast reduction[17] and nanoparticles concentrations were >10^6 particles/cm^3 in 6 different surgeries.[18]

A National Institute for Occupational Safety and Health (NIOSH) Hazard Controls publication (1996) recommended the use of LEV smoke evacuators[19] and room suctions as the primary control measures, but these controls are not consistently used. Surveys of surgical smoke control practices found that fewer than half of the medical facilities surveyed used engineering controls for reduction of surgical smoke during procedures.[20,21] This deficit is attributable to the expense and inconvenience of applying control systems (e.g., noise, distraction, and ergonomic difficulties)[22] and the fact that health effects of surgical smoke are often subtle and may not be immediate. Even when LEV is used during surgery, particles and/or VOCs may remain airborne at significant concentrations.[23,24] The Health and Safety Executive conducted an extensive literature review regarding surgical smoke exposure and its health effects but many studies were small-sized experimental measurements and did not assess personal exposure of OR workers.[5] In addition, few studies evaluated airborne particle concentrations in different particle size ranges (i.e., from nm to μm) or simultaneously measured VOC levels. Questions still remain about the residual air quality in ORs when LEV is employed.

The present experimental study aimed to compare airborne particles and levels of selected VOCs with and without LEV controls while surgical smoke is generated in an experimental situation with an electrocautery device.

Method

Generation of surgical smoke and local exhaust ventilation

Human tissues obtained from the West Virginia University (WVU) tissue bank were used to generate surgical smoke in unoccupied operating rooms at the WVU hospitals. Surgical smoke was generated with an electrocautery surgical device (model: ForceFX, Valleylab, Boulder, CO; output power of cut and coagulate were set at 35 watts) for 15 min. The activated (a mixed use of cut or coagulate mode) electrocautery stainless steel blade was contacted to the tissue and the blade was moved to fresh part of the tissue after approximately 5–10 sec of smoke generation. Two different LEV controls were utilized during smoke generation: (1) a wall irrigation suction unit with an in-line ultra-low penetration air (ULPA) filter (model: BILF150, Buffalo Filter, Lancaster, NY; filtration of 0.1 micron-sized matter at 99.9999% efficiency)[25] positioned between the wall suction units and suction canisters; and (2) a smoke evacuation system (model: PlumeSafe®Turbo, Buffalo Filter, Lancaster, NY); a four-stage filter consisting of a pre-filter, charcoal, ULPA filter and post filter (ViroSafe® filter, model: VSXLLT, Buffalo Filter) was installed in the PlumeSafe®Turbo and a vacuum hose (VT10324, 2.2 cm diameter, Buffalo Filter) was connected. Flow rate of both LEVs was approximately 35 L/min (the standard setting during normal operation at the hospitals). The distance between the electrocautery interaction site and LEV suction tip or tubing was maintained within 5 cm.[26] A total of 6 experiments were carried out with 5 fibro-adipose tissues (Experiments #1, 2, 3, 4 and 6) from breast reduction and 1 below-knee amputation (Experiment #5) surgeries. Airborne particles and VOCs were collected for 45 min in 4 different test settings for each experiment: (1) background (without any activity); (2) smoke generation without LEV control; (3) smoke generation with wall irrigation suction unit control; and (4) smoke generation with PlumeSafe®Turbo evacuation system control. Background measurement was completed first to minimize contamination of the operating room and other samplings were conducted in random order.

Airborne particle measurement

Particle number and mass concentrations were measured in real time with direct reading instruments. The number concentration of particles in the size range of 0.01–1.0 μm were measured using a condensation particle counter (CPC, model 3007, TSI Inc., Shoreview, MN) every second (2,700 data points were obtained). The particle mass concentrations were measured using a light-scattering laser photometer (DustTrak DRX Aerosol Monitor, model 8534, TSI Inc.) every second. The particle size distribution of nanoparticles (size range from 10–414 nm) was measured by a scanning mobility particle sizer (SMPS, model 3034, TSI Inc.) in 2-min intervals (a total of 20 different particle size distributions were measured). The particle size distribution in the size range of 0.5–20 μm was determined with an aerodynamic particle sizer (APS, model 3321, TSI Inc.) in 1-min intervals. Biological particle number concentrations and size distributions in the size range between 0.5 and 25 μm were measured using a BIOTRAK real-time viable particle counter (model 9510-BD, TSI Inc.) in 1-min intervals. BIOTRAK measures the fluorescence of individual aerosol particles in the wavelength range of 420–575 nm after excitation by an ultraviolet laser at 355 nm.[27] Inhalable size selective samplers (IOM sampler, SKC Inc., Eighty Four, PA) loaded with polycarbonate filters (pore size 2 μm) were utilized to collect airborne inhalable particles near the operating table (area and personal sampling). The desiccated and coated with gold and platinum sample filters were examined by a field emission scanning electron microscope (SEM; model S-4800–2, Hitachi High Technologies America Inc.) to investigate morphological characteristics of airborne particles along with elemental analysis by X-rays. All direct reading instruments were placed next to the operating table and the distance between the electrocautery interaction site and air sampling inlets was less than 45 cm.

VOCs sampling and analysis

Volatile organic compounds were collected using evacuated canisters following the NIOSH draft canister method for VOCs in air.[28] Area and personal sampling were conducted using 6 L (SilicoCan, Restek Corporation, Bellefonte, PA) and 600 mL (Silonite miniCans with Micro-QT Valves, Entech Instrument Inc., Simi Valley, CA) canisters, respectively. Passive air sampling apparatus with critical orifice (Restek Corporation) or sapphire restrictors (Restek Corporation) were utilized to maintain the flow rates of the canisters. The flow rates of 6 L and 600 mL of the canisters were 100 and 15 mL/min, respectively. Four 6 L evacuated canisters for area sampling were located around the operating table. Three evacuated canisters for personal sampling from persons present during the experiment were mounted in a holster attached to a belt fastened around the waist. To maintain the flow rate of the canisters (sampling volume should be less than 90% of the volume of the canister), the sampling times of the 6 L and 600 mL canisters were 45 and 30 min, respectively. A grab sampling technique of filling canisters within 1 min was utilized to collect VOCs within 5 cm of electrocautery interaction site. The canister samples were analyzed using a pre-concentrator (7200, Entech Instrument Inc.) and gas chromatography-mass spectrometry (Agilent Technologies, Inc., Santa Clara, CA) system pursuant to a recently published method validation study.[28,29] The study quantified VOCs associated with surgical smoke and adverse health effects commonly found in healthcare settings including α-pinene, acetone, benzene, chloroform, ethanol, ethyl benzene, hexane, isopropyl alcohol, *d*-limonene, m, p-xylene, methyl methacrylate, methylene chloride, o-xylene, and toluene.

Three additional VOCs were added to the target list for this study: acetaldehyde, acetonitrile, and styrene. Other VOCs were qualitatively identified by comparing their mass spectra to the NIST 2008 Mass Spectral Library. They were included if the quality factor of comparison was >90%. Field blank samples were collected.

Statistical analysis

The analysis for this article was generated using [SAS/STAT] software, Version 9.3 of the SAS System for Windows (SAS Institute Inc., Cary, NC). Smoke alleviation methods were compared using the Kruskal–Wallis nonparametric analysis of variance followed by Wilcoxon two-sample test for pairwise comparisons. All differences were considered significant at $p < 0.05$.

Results

Airborne particle measurement

Condensation particle counter—The airborne particle number concentrations of background, without LEV control, control with the wall irrigation suction unit, and control with the PlumeSafe®Turbo measured with the CPC in experiment #1 during 45 min sampling are shown in Figure 1a. The average particle number concentration and standard error measured with the CPC for each experiment, along with the average of all 6 experiments are shown in Figure 1b. The average is an arithmetic mean of the particle number concentration during 45 min of sampling (15 min with smoke generation and 30 min without generation). The average number concentration during the smoke generation period (15 min) was approximately 2 times larger than the average of total sampling (45 min) in all experiments. For example, the average particle number concentration in 15 min was 12,700 particles/cm^3 in experiment #1, while the average in 45 min was 5,800 particles/cm^3. The maximum particle concentration was 510,000 particles/cm^3 in experiment #2 without LEV control, which is 520 times higher compared to the average background particle concentration (~1,000 particles/cm^3). The largest 45-min average particle number concentration was found without LEV control (8,700 particles/cm^3) followed by control with the wall irrigation suction unit (1900 particles/cm^3) and control with the PlumeSafe®Turbo (1600 particles/cm^3). Average particle concentration of without LEV control was significantly larger than those of the background, control with the wall irrigation suction unit, and control with the PlumeSafe®Turbo and no significant difference was found in average concentrations of background, control with the wall irrigation suction unit, and control with the PlumeSafe®Turbo in accordance with the Wilcoxon two-sample test. The average particle number concentration ratio of without LEV control to background ranged from 3–730 with an average of 250 (a geometric mean ratio of 36). Two large ratios (730 and 724) were found in experiments #4 and #5 due to low background particle number concentrations in the operating rooms (experiment #4: 8 particles/cm^3 and #5: 1 particle/cm^3). Although the smoke generation rate between the experiments was not identical, in order to estimate effectiveness of the LEV control systems, the average particle number concentrations with and without LEV controls were compared. Ratios between average particle concentration of control with wall irrigation suction and without LEV ranged from 0.04–0.64 with average of 0.33 ± 0.21. Ratios between average particle number concentration of control with the PlumeSafe®Turbo and without LEV ranged from 0.08–0.49 with an average of 0.24 ± 0.16.

Scanning mobility particle sizer

Particle size distributions of particles ranging from 10–414 nm measured with the SMPS in experiment #3 are shown in Figure 2, where each distribution is an average of 20 distributions for each test setting. Due to a malfunction of the SMPS, particle size distributions in experiment #2 were not obtained. The average particle size distributions in other experiments were similar to that in experiment #3 (data not shown). The average count median diameters (CMD) of background, without LEV control, control with the wall irrigation suction unit, and control with the PlumeSafe®Turbo were 64, 85, 77, and 30 nm, respectively. Average particle number concentrations measured by the SMPS were 8,100 particles/cm^3 without LEV control, 3,500 particles/cm^3 with the wall suction unit control, and 2,000 particles/cm^3 with the PlumeSafe®Turbo control, which are comparable to the concentrations from the CPC. Average total concentrations between the test settings were compared and background vs. without LEV control, without LEV control vs. control with the wall irrigation suction unit and without LEV control vs. control with the PlumeSafe®Turbo showed significantly difference. Ratios between the average particle concentrations of control with the wall irrigation suction unit and without LEV ranged from 0.18–0.67 with an average ratio of 0.39 ± 0.18. Ratios between the average particle number concentrations of control with the PlumeSafe®Turbo and without LEV ranged from 0.05–0.58 with an average ratio of 0.28 ± 0.27.

Light-scattering laser photometer

The average mass concentrations and standard error measured with the DustTrak DRX for each experiment along with the average of 6 experiments are shown in Figure 3. The average mass concentration levels were generally below 40 μg/m^3 due to the small particle sizes of most of the airborne particles. The largest average mass concentration was found without LEV control (21 μg/m^3), followed by control with the wall irrigation suction unit (7 μg/m^3), and control with the PlumeSafe®Turbo (3 μg/m^3). The maximum mass concentration was 830 μg/m^3 in experiment #2 without LEV control. Average mass concentration of without LEV control was significantly larger than those of the background, control with the wall irrigation suction unit, and control with the PlumeSafe®Turbo and no significant difference was found in average concentrations of background, control with the wall irrigation suction unit and control with the PlumeSafe®Turbo. Average mass concentration ratio of without LEV control to background ranged from 2–41 with an average ratio of 15 (a geometric mean ratio of 9). Ratios of average mass concentration of control with the wall irrigation suction unit to without LEV control ranged from 0.06–0.59 with average ratio of 0.31 ± 0.18. Ratios of average mass concentration of control with PlumeSafe®Turbo to without LEV control ranged from 0.04–0.35 with average ratio of 0.14 ± 0.12.

Aerodynamic particle sizer and BioTrak

Particle size distributions in the particle size range of 0.5–20 μm measured with the APS in experiment #3 are shown in Figure 4, and each distribution shown is an average of 45 distributions for each test setting. The average particle size distributions in other experiments were similar to those in experiment #3 (data not shown). The average count median aerodynamic diameters (CMAD) of background, without LEV control, control with the wall suction unit and control with the PlumeSafe®Turbo were 0.68, 0.71, 0.69, and 0.73 μm, respectively. The average particle number concentration measured by the APS was 19 particles/cm^3 without LEV control, 11 particles/cm^3 with the wall suction unit control, and 8 particles/cm^3 with the PlumeSafe®Turbo control. No significant difference was found between test settings ($p > 0.05$). Ratios of the average particle number concentrations of control with the wall irrigation suction unit to without LEV control ranged from 0.31–1.1 with an average ratio of 0.55 ± 0.30. Ratios of the average particle number concentrations of control with the PlumeSafe®Turbo to without LEV control ranged from 0.002–0.52 with an average ratio of 0.26 ± 0.23.

The average viable particle number concentration measured with the BioTrak was 0.0017 particles/cm^3 without control, 0.00053 particles/cm^3 with the wall suction irrigation unit control, 0.00028 particles/cm^3 with the PlumeSafe®Turbo control. The average viable particle fraction in total airborne particles in size ranges 0.5–20 μm ranged from 0.06–0.21%.

SEM analysis

Qualitative SEM analysis was conducted in a total of 45 samples from the IOM sampler, and an example of a particle is shown in Figure 5 along with qualitative elemental counts by energy-dispersive X-ray spectrometry. The particles were amorphous in shape and had similar X-ray elemental distributions. At least 25 particles were identified in each sample, and particles were not densely populated. Airborne particles in the micrometer size-range were observed in all test settings but particles in nanometer sizes were not identified. It may be that most of the airborne particles were water or steam from cellular fluid from adipose tissues, which would not be visible under the electron microscope.

VOCs

The average concentrations (μg/m^3) of VOCs sampled with evacuated canisters for each test setting are shown in Table 1, along with recommended exposure limits (REL) from the National Institute for Occupational Safety and Health (NIOSH Pocket Guide to Chemical Hazards, 2007).[30] In general, concentrations of the VOCs were much less than the NIOSH REL values (3–5 orders of magnitude less). Ethanol and isopropyl alcohol were predominantly detected in every sample with relatively high concentrations (~1300 μg/m^3) compared to other VOCs. No α-pinene was detected. In general, high concentrations of VOCs were quantified in samples without LEV control, especially samples with grab sampling, relative to background and controls with the LEV systems. No benzene, o-xylene, and styrene were detected in background samples while these VOCs were detected in samples without LEV control and some in samples with LEV controls indicating those VOCs may be mainly from surgical smoke generation. Concentrations of acetaldehyde, acetone, acetonitrile, and ethanol without LEV controls were significantly higher than background concentrations while toluene, n-hexane and isopropyl alcohol were not. The average canister sample results of without LEV control, control with the wall irrigation suction unit and control with the PlumeSafe®Turbo were compared in each sampling technique (grab, personal and area sampling) and ratios (control with the wall irrigation suction unit/without LEV control and control with the PlumeSafe®Turbo/without LEV control) are shown in Table 2 (average background were subtracted from each sampling technique). The ratios of acetone, d-limonene, ethanol, and isopropyl alcohol were higher, and these chemicals may arise from use commonly used for disinfecting and cleaning products in operating room. The ratios of methylene chloride and styrene were not available because they were not detected when both controls were utilized. A total of 50 VOCs were qualitatively identified in the mass spectra and sevoflurane and isoflurane, inhalational anesthesia, were the most frequently detected VOCs.

Discussion

Airborne particle concentration and LEV control

Although the levels of smoke generated in these experiments do not represent an actual operating procedure, particle concentrations measured with direct reading instruments were comparable to previously reported values. Average particle number concentrations measured with a CPC in 6 different surgeries without LEV control ranged from 74–12,200 particles/cm^3.[18] Ultrafine particle concentrations measured with a fast mobility particle sizer in 5 different surgical procedures with LEV controls were in the range of 300–3900 particles/cm^3.[31] Airborne particles were measured with a laser particle counter (particles in μm size range) during mammoplasty-related procedures with and without LEV system control, and the particle number concentration was 10^6 particles/ft^3 (35 particles/cm^3) without control. The LEV systems reduced particles >50% and residual particles remained in the ORs.[23,24] Average mass concentrations measured with a DustTrak with and without LEV controls in anterior cervical collar incisions (15 cases each) were 0.012 and 0.137 mg/m^3, respectively, and the smoke evacuation system reduced the smoke about 90%.[32] Airborne particle number (ultra-fine particles measured using a P-Trak) and mass concentrations (respirable size fraction measured with a DustTrak) differed between peritonectomy cases (higher voltage of electrocautery device recommended) and standard colon and rectal cancer surgeries with LEV controls. Median particle number concentrations were 800 particles/cm^3 for peritonectomy and 250 particles/cm^3 for standard surgery and median mass concentrations were in range of 2–9 μg/m^3.[33] The differences in airborne particles number and mass concentrations between the studies may be attributable to different evacuation systems with different suction flow rates, surgery type, ventilation rate of the operating rooms, power level of electrocautery device, and tissue type. When smoke control at a flow rate of 1,400 L/min^1 (velocity around 150 ft/min^1) was placed within 5 cm of the laser interaction site, smoke was removed completely.[26] However, airborne particle concentration was measured using a photometer possibly resulting in underestimation of ultrafine particles and the flow rate of the evacuation system was 40 times higher than the present study. The wall irrigation suction unit and the PlumeSafe®Turbo require an experienced assistant to hold either the suction tip or tubing and may be difficult to maintain the distance. In addition, the suction tip or tubing may obstruct the surgeons' view and suggesting these types of control may not be a long-term solution for control.[26,32] Based on the previous and present studies some surgical smoke remains when LEV controls are in place. To increase protection, respirators with a higher protection factor than a surgical mask and different designs of smoke evacuation systems may need to be evaluated. A recent study found that N95 surgical mask respirators showed about a 200 times higher simulated workplace protection factor (ratio of particle number concentration in and out of the mask) than standard surgical masks in 10 human subjects.[34] In addition, there are other commercial devices that are designed to be close to the site of smoke generation to provide continual evacuation, for example, a electrocautery pen with an attached suction fitting[25] and a pre-sterilization smoke capture device[35] that can be applied near incision area. Teflon-coated blades and feedback mode (reducing output power automatically in response to impedance) were able to reduce the amount of surgical smoke compared to stainless steel blades and pure-cut mode.[36]

VOCs

LeBouf et al. reported exposures to VOCs among 14 health care occupations. Geometric mean personal exposure levels among surgical technologists were generally lower than in the present study.[29] Variations in sampling strategy could account for the differences, i.e., full-shift sampling vs. 45 min sampling. Likewise, the average concentrations in grab samples were generally higher than in personal and area samples. The VOCs in the personal and area samples were diluted in air due to a relatively high air exchange rate in the ORs (minimum 15 exchanges/h).[15] Sagar et al. reported maximum levels of VOCs in 6 different surgeries including benzene (71 μg/m^3), ethyl benzene (36 μg/m^3), styrene (21 μg/m^3), carbon disulfide (1.5 μg/m^3), and toluene (460 μg/m^3) without LEV control.[37] Since tissue types, surgical technique, and types and energy levels of surgical devices may affect the levels and composition of VOCs, results can vary greatly between studies. A cross-sectional study reported a risk for developing respiratory symptoms, including the sensation of a lump in the throat and sore throat in third-year residents exposed to surgical smoke.[38] OR nurses are also at high risk of severe persistent asthma due to exposure to disinfectants and cleaning agents.[39] Many VOCs were not detected in both the evacuated canister samples in the present study. This result might be attributable to low concentrations of VOCs due to short periods of smoke generation, as well as dilution factors. The use of electrocautery in real operating procedures would be longer in duration than the present study. Although electrocautery duration is dependent on surgery type, some procedures, including mammoplasty and nephrectomy, involved approximately 60 min of electrocautery[23,31] or less.[31,40] A formal investigation of personal exposure levels of airborne surgical smoke in actual surgeries is an ongoing process.

Conclusion

Based on the findings from the present experimental study, utilization of the LEVs for surgical smoke control can significantly reduce but not completely eliminate airborne particles and VOCs. LEV systems should be used to increase protection of operating room workers from surgical smoke exposure, and more effective LEV devices may need to be evaluated.

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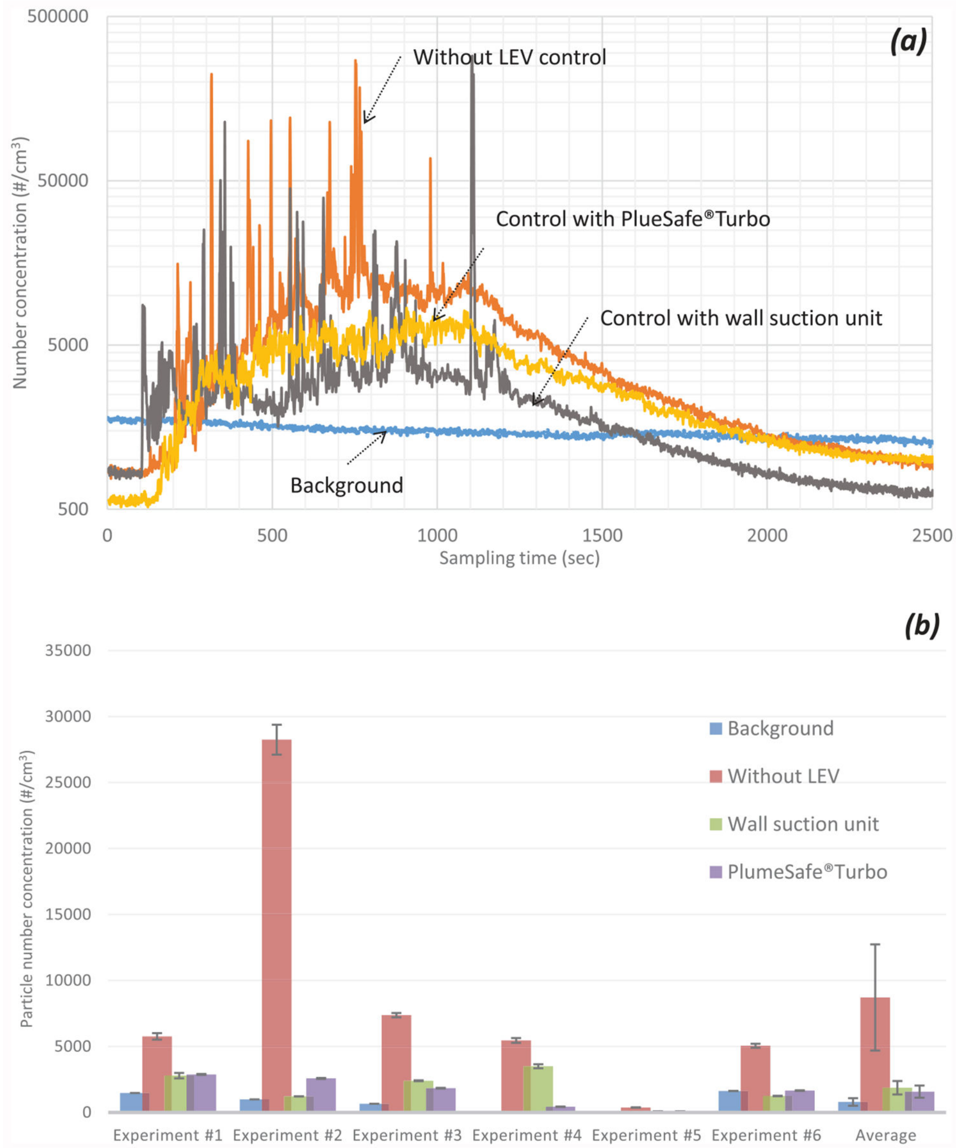

Figure 1.

(a) Particle number concentration measured with a condensation particle counter in background, without LEV, control with wall suction unit, and control with PlumeSafe®Turbo in experiment #1. Scale of the y-axis (number concentration/cm^3) is logarithmic. (b) Average particle number concentration (particles/cm^3) and standard error measured with a condensation particle counter for each experiment and average of all experiments.

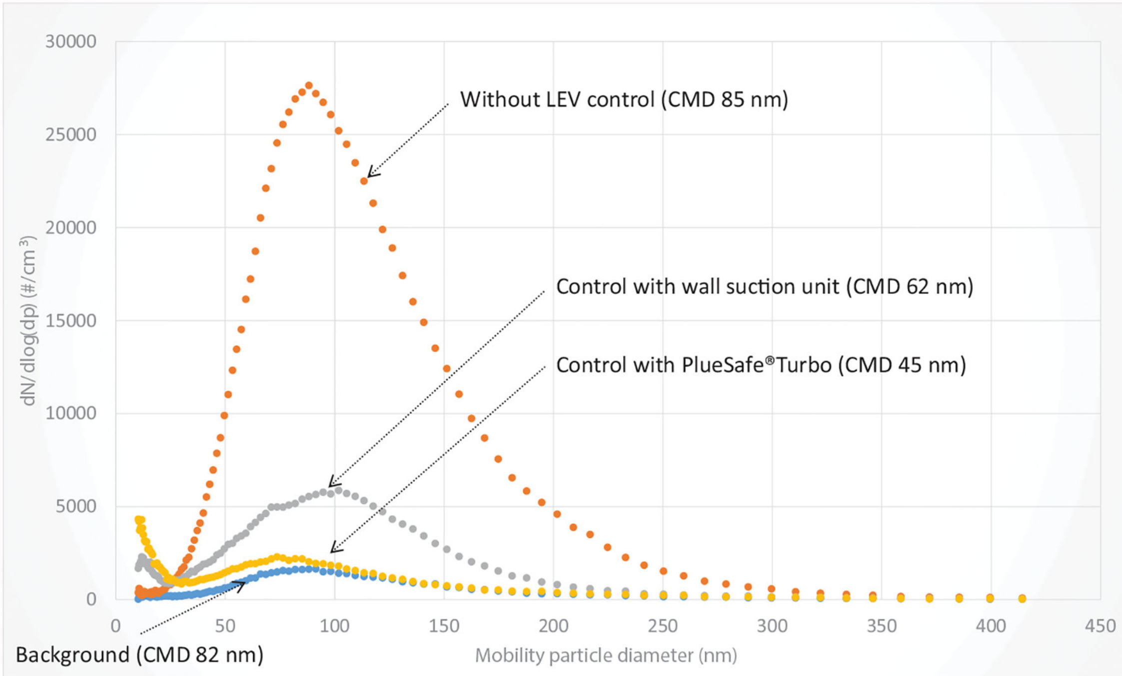

Figure 2.

Average number weighted particle size distributions measured with a Scanning Mobility Particle Sizer for experiment #3. CMD is count median diameter and it is an average of 20 particle distributions.

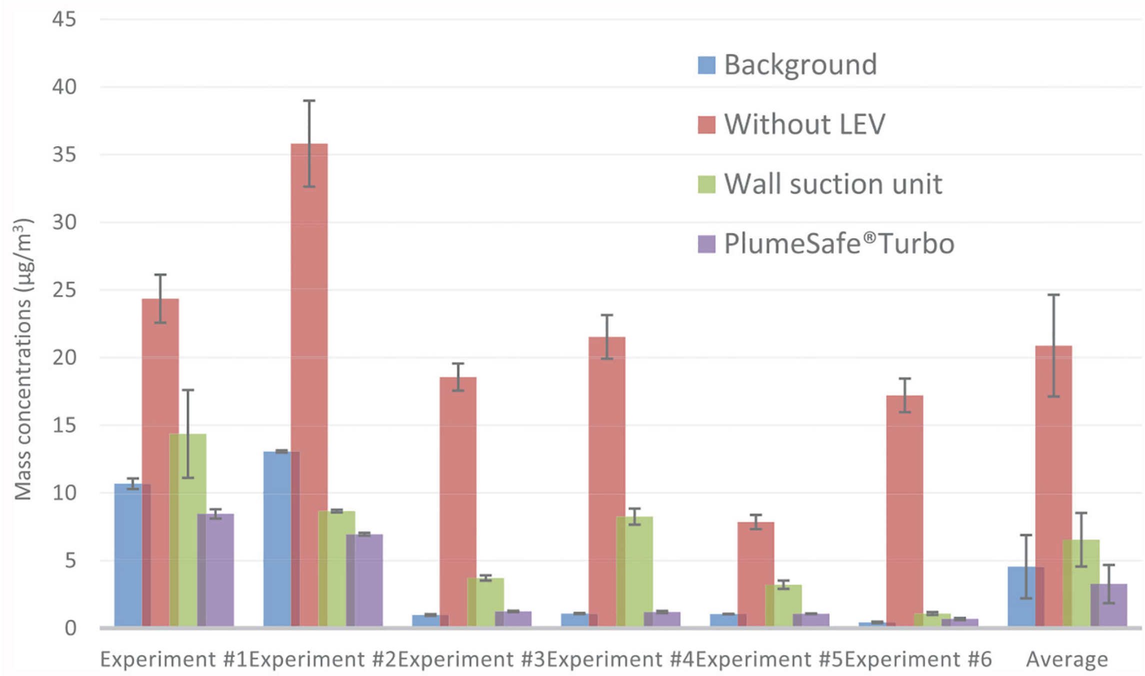

Figure 3.

Average particle mass concentration (μg/m^3) and standard error measured with a light-scattering laser photometer (size range: total) for each experiment along with average of all experiments.

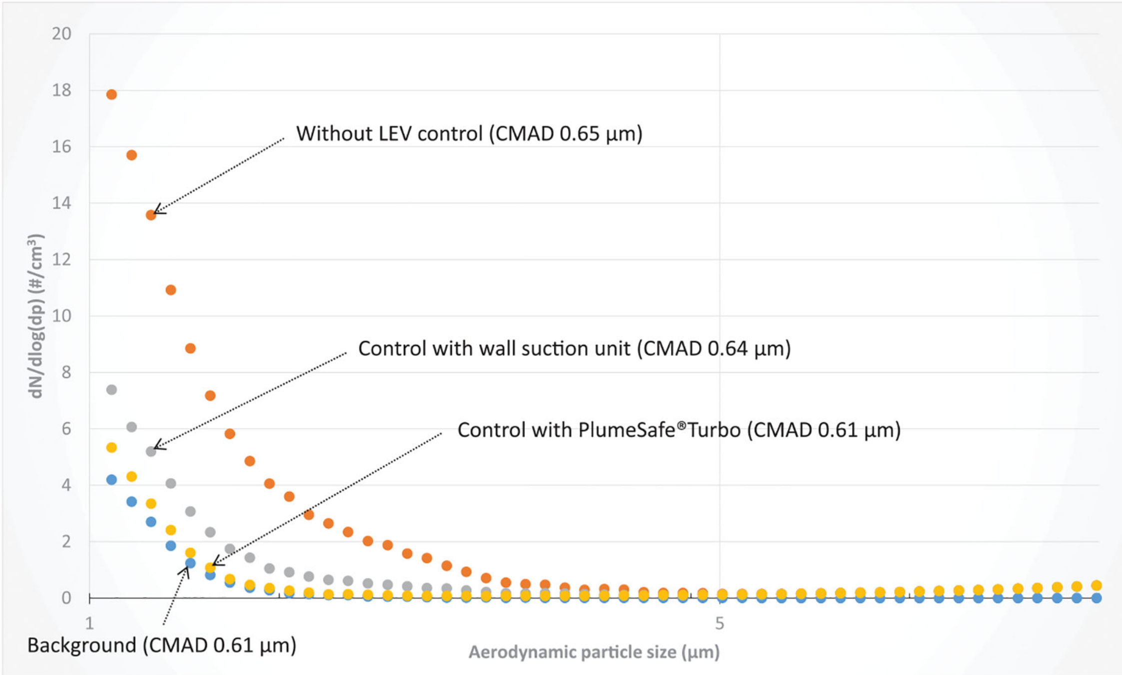

Figure 4.

Average number weighted particle size distributions measured with an Aerodynamic Particle Sizer in experiment #3. The largest particle concentration was selected in 45 different measurements. CMAD is count median aerodynamic diameter.

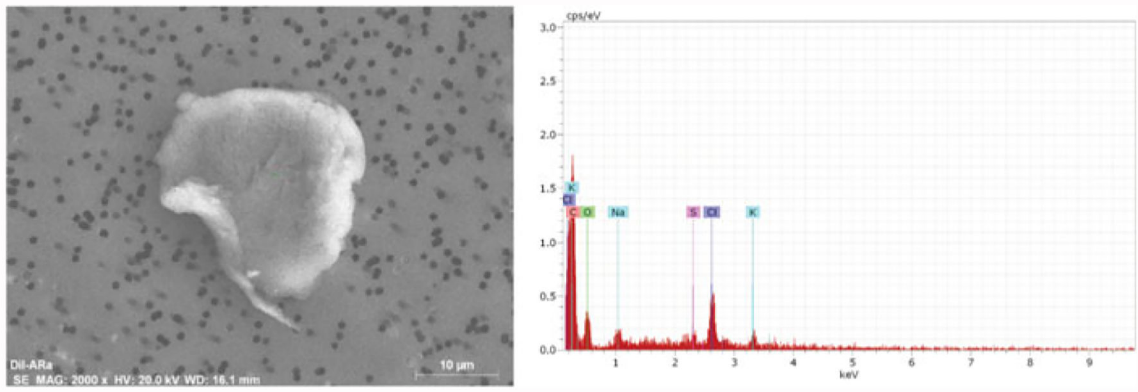

Figure 5.

Airborne particle with SEM image along with X-ray counts.

Table 1.

Average concentrations (μg/m^3) (standard error) of volatile organic compounds from surgical smoke.

		Background			Without control			Control with wall irrigation suction unit			Control with PlumeSafe® Turbo		
VOCs	**REL (μg/m^3)**	**GS**	**PS**	**AS**	**GS**	**PS**	**AS**	**GS**	**PS**	**AS**	**GS**	**PS**	**AS**
Acetaldehyde	lowest feasible	12 (6)	19 (2)	12 (4)	430 (194)	39 (10)	27 (14)	45 (39)	24 (2)	13 (1)	22 (8)	28 (5)	13 (1)
Acetone	590,000	17	40 (8)	27 (17)	55 (26)	82 (10)	21 (4)	24 (13)	59 (9)	25 (5)	42 (19)	68 (7)	26 (2)
Acetonitrile	34,000	9 (3)	6 (2)	9 (3)	57 (17)	8 (2)	16 (5)	7 (2)	7 (1)	9 (1)	12 (5)	8 (1)	8 (1)
α-Pinene	—	—	—	—	—	—	—	—	—	—	—	—	—
Benzene	3,190	—	—	—	110 (84)	16	26 (26)	26 (26)	—	—	56	—	—
Chloroform	9,780	—	2	—	—	6(6)	2	1	—	—	—	1	1
d-Limonene	—	7	—	—	13	12 (7)	10 (1)	8	17 (7)	11 (1)	—	17 (2)	25 (10)
Ethanol	1,900,000	810 (343)	750 (189)	870 (326)	1200 (635)	850 (149)	1100 (173)	540 (172)	810 (165)	1000 (132)	1200 (487)	710 (109)	880 (110)
Ethylbenzene	435,000	3	2	—	10 (4)	18	5	4	6	5	—	—	4
Isopropyl Alcohol	980,000	850 (220)	800 (157)	740 (248)	600 (168)	1200 (256)	1200 (265)	840 (291)	1100 (232)	1200 (219)	1300 (499)	1100 (144)	780 (103)
m,p-Xylene	435,000	3	2	—	5 (1)	15	4	3	5	4	—	—	4 (1)
Methyl methacrylate	410,000	4	4	—	15	11 (5)	16 (3)	4 (1)	6	—	—	5 (1)	—
Methylene chloride	lowest feasible	—	2	—	—	15 (12)	—	—	—	—	—	—	—
n-Hexane	180,000	3	32 (15)	50	23 (15)	17 (6)	15 (4)	8 (5)	5 (1)	5	9	25 (4)	20 (5)
o-Xylene	435,000	—	—	—	2	11 (8)	—	—	2(1)	—	—	3 (1)	—
Styrene	215,000	—	—	—	13 (6)	20	7	—	—	—	—	—	—
Toluene	375,000	4	67 (64)	210	30 (17)	7 (2)	9 (2)	16	9 (2)	10 (1)	18 (13)	16 (7)	25 (8)

GS: grab sampling, PS: personal sampling, AS: area sampling, -: non-detected.

REL: Recommended exposure limits from National Institute for Occupational Safety and Health.

Table 2.

Ratios of average VOCs concentration.

Volatile organic compounds	Control with wall irrigation suction/without LEV control			Control with PlumeSafe®Turbo/without LEV control		
	GS	PS	AS	GS	PS	AS
Acetaldehyde	0.08	0.25	0.07	0.02	0.45	0.07
Acetone	0.18	0.45	0.33	0.66	0.67	0.17
Acetonitrile	*	0.79	**	0.06	1.43	*
α-Pinene	**	**	**	**	**	**
Benzene	0.24	0.01	**	0.51	0.01	**
Chloroform	**	*	**	**	*	0.41
d-Limonene	0.14	1.42	1.16	*	1.42	2.63
Ethanol	*	0.60	0.57	1.00	*	0.04
Ethylbenzene	0.05	0.22	0.90	*	*	0.80
Isopropyl Alcohol	0.04	0.75	1.00	*	0.75	0.09
m,p-Xylene	0.08	0.23	0.97	*	*	1.03
Methyl methacrylate	0.04	0.25	**	*	0.10	**
Methylene chloride	**	*	**	**	*	**
n-Hexane	0.23	1.83	1.29	0.26	0.47	0.86
o-Xylene	**	0.20	**	**	0.28	**
Styrene	**	**	**	**	**	**
Toluene	0.46	0.97	1.00	0.54	0.85	0.92

GS: grab sampling, PS: personal sampling, AS: area sampling.

* Average background concentration is larger than average concentration of VOC.

** Below detection limit or not detected.