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Evaluation of Personal Exposure to Surgical Smoke Generated from Electrocautery Instruments: A Pilot Study

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Abstract

Hospital technician surgical smoke exposures during several types of electrocautery-based procedures were evaluated. Personal and area air sampling was performed for 106 individual analytes including ultrafine particulate matter (UFP), volatile organic compounds, polycyclic aromatic hydrocarbons, phenol, aldehydes, carbon monoxide, hydrogen sulfide, and hydrogen cyanide. Acetone, D-limonene, ethanol, ethyl acetate, and fluorene were measured in surgical suites at concentrations 1.1- to 3.7-fold higher than those observed in background. Benzene, α-pinene, methylene chloride, and *n*-hexane were measured in the absence of a detectable background concentration. All analytes were measured at concentrations that were <1% of the corresponding US federal and state 8-h permissible exposure limits (PELs), if PELs existed. Full-shift average UFP concentrations ranged from 773 to 2257 particles/cm^3, approximately one order of magnitude higher than surgical suite background concentrations. A comparison of two breast reduction procedures suggested that the use of smoke evacuators reduced UFP exposure by 6-fold. We concluded that selection and evaluation of key hazards, particularly UFP, under a variety of experimental conditions would be beneficial to elucidate potential health effects and causes osf employee complaints. Recommendations for successful sampling campaigns in future surgical smoke occupational exposure studies are provided. We also recommend the continued use of engineering controls, local exhaust ventilation, and surgical N95 respirators to reduce personal exposures to UFP in surgical smoke.

Keywords: full-shift monitoring; industrial hygiene; surgical plume; surgical smoke; ultrafine particulate matter; VOCs

Introduction

Surgical smoke is a visible suspension of water vapor, volatile organic compounds (VOCs) and other organic matter of biological origin released when energy-generating medical instruments raise intracellular temperatures >100°C (Munro, 2012). Exposure to respiratory irritants, biologically active particulates, and potential carcinogens contained in surgical smoke (or surgical plume) has been a clinical concern since the 1970s (Novak and Benson, 2010). A variety of instruments including laser, electrosurgical, electrocautery, and ultrasonic ablation devices are capable of generating surgical smoke in the operating theater. In this study, we focused on electrocautery instruments, which generate heat to burn or coagulate tissue by passing an electrical current through a resistant metal electrode. These instruments are ubiquitous in modern surgical procedures performed by ear, nose and throat specialists, dermatologists, ophthalmologists, plastic surgeons, urologists, surgical oncologists, and other specialist surgeons.

Prior peer-reviewed and National Institute for Occupational Safety and Health (NIOSH) Health Hazard Evaluations (HHEs) studies of electrocautery smoke constituent exposures have varied appreciably by the type of air sampling performed, type of animal or human tissue operated on during surgery, the airborne agents assessed, and the airborne agents detected (Table 1). Similar variability in selection and detection of target analytes exists among studies focused on live human surgeries compared to simulated surgeries. The most commonly detected constituents have included VOCs (Bryant et al., 1988; Sagar et al., 1996; Wu et al., 1997; Hensman et al., 1998; DeHaan et al., 2004; Hollmann et al., 2004; King and McCullough, 2006a,b,c; Al Sahaf et al., 2007; Krones et al., 2007; Moot et al., 2007; Rey et al., 2008; Chung et al., 2010; Lin et al., 2010; Choi et al., 2014; Choi et al., 2018; Lee et al., 2018), particulate matter [$PM_{2.5}$ and/or ultrafine particulate matter (UFP)] (Bryant et al., 1988; King and McCullough, 2006a,b,c; Brüske-Hohlfeld et al., 2008; Näslund Andréasson et al., 2012; Wang et al., 2015, Elmashae et al., 2018; Lee et al. 2018), aldehydes (Hensman et al., 1998; DeHaan et al., 2004; Hollmann et al., 2004; King and McCullough, 2006a,b,c; Krones et al., 2007; Moot et al., 2007; Lee et al. 2018), and hazardous gases (e.g. ammonia, hydrogen cyanide, carbon monoxide) Wu et al., 1997; Hollmann et al., 2004; Krones et al., 2007; Moot et al., 2007; Rey et al., 2008).

At the time of our initial study design (July 2016), no study had presented industrial hygiene sampling data representative of full-shift clinical exposures from consecutive live human surgeries. In addition, most studies focused on source characterization (Sagar et al., 1996; Hollmann et al., 2004; Al Sahaf et al., 2007; Chung et al., 2010; Lin et al., 2010; Choi et al., 2014; Wang et al., 2015) or used an animal or human tissue simulation protocol (Wu et al., 1997; Hensman et al., 1998; DeHaan et al., 2004; Krones et al., 2007; Rey et al., 2008), with a minority of studies measuring analytes in the worker's breathing zone or using area samples to approximate a worker's breathing zone (Bryant et al., 1988; King and McCullough, 2006a,b,c; Moot et al., 2007; Brüske-Hohlfeld et al., 2008; Näslund Andréasson et al., 2012). Source characterization studies consist of protocols intended to capture surgical smoke directly in whole air sampling bags, within the smoke evacuation system itself, or within centimeters of the tip of the smoke generating electrocautery devices. The source characterization methodologies provide useful information regarding potential chemical and particulate content of electrocautery surgical smoke but cannot be used to characterize personal exposures to surgeons or surgical technicians.

The objective of this pilot study was to evaluate the usefulness of various sampling methods for characterization of full-shift personal exposures to surgical smoke generated by the use of electrocautery instruments. Notably, we are unaware of published guidance supporting the design and execution of full-shift industrial hygiene sampling campaigns focused on surgical smoke monitoring during electrocautery surgeries. Therefore, the methodological considerations of 'real-world' sampling in a live clinical setting during the routine performance of common medical procedures were of particular interest in the pilot study design.

Methods

This pilot study was designed as an industrial hygiene survey of hospital surgical technicians. Surgical technicians were defined as surgical team members who remained in their designated workspace around the surgical table throughout the procedure. Potential exposures experienced by surgeons, anesthesiologists, and circulating nurses were not considered for this pilot study. We did not collect personal samples on the surgeons as they performed delicate procedures on patients and we were unable to assure that the equipment would not interfere with patient care. Anesthesiologists largely worked outside of the immediate surgical area. Finally, the circulating nurses moved in and out of the surgical area to provide appropriate tools. Air sampling

Table 1. NIOSH HHEs that have identified and/or quantified constituents of surgical smoke generated during procedures that used electrocautery devices.

Reference	Animal/human	Sample location	Airborne species detected
Live surgeries			
Bryant et al., 1988	Human	Personal breathing zone of unknown personnel; area samples of unknown distance	Benzene soluble fraction of particulate, total particulate, hydrocarbons, and compounds related to fatty acid esters
Sagar et al., 1996	Human	At the tip of the device or held in plume above device	Benzene, ethylbenzene, styrene, carbon disulfide, toluene
Hollmann et al., 2004	Human	2 cm from tip of device	1-Ethenyl-3-methyl-benzene, 1,3-butadiene, propanenitrile, toluene, thiocyanic acid, 1-heptene, ethylene, ammonia, 1-decene, 2-furancarboxaldehyde (furfural), methylpropene
King and McCullough, 2006a	Human	Personal breathing zone of one person at surgical table and one person stationed at periphery of room; area samples several feet from the surgical table at shoulder height	Formaldehyde, acetaldehyde, toluene, particulate matter
King and McCullough, 2006b	Human	Personal breathing zone of one person at surgical table and one person stationed at periphery of room; area samples several feet from the surgical table at shoulder height	Formaldehyde, acetaldehyde, toluene, particulate matter
King and McCullough, 2006c	Human	Personal breathing zone of one person at surgical table and one person stationed at periphery of room; area samples several feet from the surgical table at shoulder height	Formaldehyde, acetaldehyde, toluene, particulate matter
Al Sahaf et al., 2007	Human	In the device suction extraction system	Cyclohexanone, decene, decane, dodecene, dodecane, ethylbenzene, heptanal, nonanal, *n*-propylbenzene, pentadecane, perchloroethylene, tridecane, tetradecene, tetradecenetradecene, toluene, undecane, undecene, xylene
Moot et al., 2007	Human	< 2 cm from pencil; tubing attached to headlight of surgeon (personal breathing zone)	Hydrogen cyanide, acetylene, 1,3-butadiene, furancarboxaldehyde (furfural), 1-decene, propanenitrile
Brüske-Hohlfeld et al., 2008	Human	Equipment on anesthetist side and tubing fixed to middle of surgical cover 'sticking out about 5 cm corresponding roughly to the breathing zone of the surgical personnel'	UFP
Näslund Andréasson et al., 2012	Human	2–3 cm from the breathing area of the surgeon, 3 m from the incision point, and 2 m from the back of the smoke evacuation generator and the outflow of the filtered smoke	UFP
Lin et al., 2010	Human	2–3 cm from tip of the instrument	Toluene
Chung et al., 2010	Human	Bladder (Tedlar gas bag)	Propene, propadiene, isobutylene, 1,3-butadiene, vinyl acetylene, methyl mercaptan, ethylacetylene, diacethylene, 1-pentene, ethanol, piperylene, propenylacetylene, 1,4-pentadiene, cyclopentadiene, acrylonitrile, butyrolactone

Table 1. *Continued*

Reference	Animal/human	Sample location	Airborne species detected
Choi et al., 2014	Human	Abdomen (Tedlar gas bag)	Ethanol, 1,2-dichloroethane, benzene, ethylbenzene, styrene, acetone, 2-butanone, hexane, *n*-heptane, toluene, *p*-xylene, *n*-nonane, *o*-xylene, *n*-decane, *n*-undecane, *n*-hexadecane, *n*-tridecane, and *n*-tetradecane
Wang et al., 2015	Human	40, 60, and 120 cm from the incision	$PM_{2.5}$
Choi et al., 2018	Human	Source sample directly from cannula of trocar (Tedlar gas bag, pre- and post- carbon filter samples)	Ethanol, acetone, 2-butanone, hexane, 1,2-dichloroethane, benzene, *n*-heptane, toluene, ethylbenzene, *p*-xylene, styrene, *n*-nonane, *o*-xylene, *n*-decane, *n*-undecane, *n*-hexadecane, *n*-tridecane, *n*-tetradecane
Present Study	Human	Personal breathing zone of surgical technicians and area samples 0.9–2.4 m from surgical procedures	2-Propanol, acetone, alpha-pinene, benzene, dichlorodifluromethane, D-limonene, ethanol, ethyl acetate, ethylbenzene, fluorene, *m,p*-xylene, methylene chloride, *n*-butyl acetate, *n*-hexane, *o*-xylene, propene, toluene, carbon monoxide, UFP
Simulation studies			
Wu et al., 1997	Porcine	Laparoscopic trocars	Hydrogen cyanide, carbon monoxide, acrylonitrile
Hensman et al., 1998	Porcine liver	Sealed chamber	2,3-Dihydro indene, 1-decene, 1-undecene, ethynyl benzene, ethylbenzene, toluene, 3-butenenitrile, benzonitrile, 2-propylene nitrile, pyrrole, 6-methyl indole, indole, 2-methyl propanol, 3-methyl butenal, furancarboxaldehyde (furfural), benzaldehyde, 2-methyl furan, 2,5-dimethyl furan, methyl pyrazine, hexadecanoic acid, 4-methyl phenol
DeHaan et al., 2004	Chicken, porcine, and human adipose tissue	In a vial placed above the ribbon heater	Benzene, 1-heptene, *n*-pentanal, 1-octene, *n*-octane, *n*-hexanal, 1-nonene, *n*-nonane, *n*-heptanal, decadiene, 1-decene, *n*-decane, *n*-octanal, undecadiene, *n*-undecene, *n*-undecane, *n*-nonanal, 4-methyl hexanal, dodecadiene, 1-dodecene, *n*-dodecane, *n*-decanal, cyclodecene, 1-tridecene, *n*-tridecane
Krones et al., 2007	Porcine liver	50 cm (with and without off gas device)	Formaldehyde, acetaldehyde, acetone, propene, crotonaldehyde, butanol, benzaldehyde, pentanol, acrylamide, benzene, toluene, ethyl benzene, *m,p*-xylene, *o*-xylene, styrene, naphthalene, TVOCs, hydrocyanic acid, carbon monoxide, nitrous fumes, carbon dioxide

Table 1. *Continued*

Reference	Animal/human	Sample location	Airborne species detected
Rey et al., 2008	Porcine liver	Sealed chamber	Methanol, ethanol, ammonia, carbon dioxide
Lee et al., 2018	Human tissue	Unoccupied surgical suite, particulate matter collected <45 cm from electrocautery interaction site; VOCs at 5 cm, waist height (evacuated canister)	Particulate matter, ethanol, isopropyl alcohol, acetaldehyde, acetone, acetonitrile, benzene, chloroform, D-limonene, ethylbenzene, *m,p*-xylene, methyl methacrylate, methylene chloride, *n*-hexane, *o*-xylene, styrene, toluene
Elmashae et al., 2018	Lamb muscle	24 m^3 chamber; breathing zone of technician	UFP, Particulate matter

was performed in five different operating rooms during various types of surgical procedures (Table 2).

Selection of target analytes

A total of 75 VOCs commonly assessed using United States Environmental Protection Agency (US EPA) Method TO-15 were included based on widely variable VOC detections and measurements presented in the literature (Table 1). UFP, aldehydes, and selected hazardous gases were included in our study based on detection frequency and potential for suggested health effects. Phenol was included based on the potential for generation of appreciable quantities of this constituent during the burning of fat (Barrett and Garber, 2003). In addition, polycyclic aromatic hydrocarbon (PAH) sampling was included based on the potential abundance of these compounds in electrocautery smoke and the carcinogenic properties of some PAHs (Näslund Andréasson et al., 2012).

Sample collection and analysis

The sampling design included collection of full-shift personal and area samples over a 3-day period. Personal samples were collected for the following analyte groups: aldehydes, phenol, VOCs, and PAHs. Area samples were collected for the following analyte groups: UFP and hazardous gases. The results for each of the analyte groups constituted a sample set (designated 1–9). Six sample sets were collected for personnel exposure sampling, two were background sample sets, and one was a set of field blanks (Table 2).

Personal air sampling

Personal air sampling was performed for 102 individual analytes using a combination of media types including passive badges, evacuated air canisters (Summa® canisters), and personal sampling pumps with sampling media. For each type of media except the Summa canisters, a field blank was collected and stored with the completed samples until shipment.

All passive badge personal samples were collected in the breathing zone of the worker by attaching the badge with a lapel clip to the outside of the surgical gown at the nape of the neck on the collar or near the shoulder, but outside of the sterile field (a specific area kept free of microbial contamination during a surgery). Summa canisters (1.0 L) were equipped with 8-h flow controllers and then either attached to a customized belt apparatus by positioning the flow controller into a Velcro loop, or by placing it in a slim backpack. Vinyl tubing was attached to the open end of the flow controller and to the back of the technician's scrubs underneath the surgical gown. If a backpack was preferred by the participant, the tubing was threaded through the backpack, which was worn under the surgical gown. The end of the tubing was fixed to the breathing zone using a lapel clip on the outside of the surgical gown. PAH personal samples were collected by attaching a personal sampling pump to the belt, or placing it in the backpack worn under the surgical gown, and placing the sampling train in the breathing zone using a lapel clip attached to the gown near the nape of the neck. For all types of samples, study participants kept the sampling equipment on their person for the entire shift, including during breaks.

All surgical suites were occupied throughout the day at the hospital, and cauterized tissue odors were detected in hallways adjacent to the operating rooms during active procedures. To ensure an adequate characterization of background based on the available locations, sampling was performed by attaching a badge, canister or pump with sample media to an area stand in an equipment storage room inside the hospital, well-removed from the surgical suite area, at a sampling height of ~1.5 m (5 ft). The identity of each analyte, diffusive, or sampling flow rates for each analyte, and method reporting

Table 2. Outline of sample sets, types of surgical procedures ongoing during sampling, and ventilation information.

Sample set identifier	Type of samples in set[a]	Type(s) of surgical procedure[b]	Length of procedure (min)	Discrete air sample durations (min)	Real-time monitoring durations (min)	Room floor area (m^2)	Room ceiling height (m)	Air changes per hour (h^{-1})	Supply air flow rate (m^3 min^{-1})	Exhaust air flow rate (m^3 min^{-1})	Local exhaust ventilation used by surgical team
1	Hospital personnel	(i) Phalloplasty and left radial forearm flap	430	VOC: 158[c] PAH: 468 Badges: 497-498	403	60.2	2.93	24.8	76.2	40.9	Wall suction tube
2	Hospital personnel	(i) Right free latissiumus flap to left leg (ii) Urethroplasty, cystoplasty, and glansplasty	255 250	VOC: 180[c] PAH: 296[d] Badges: 489-492	[5][f]	59.2	2.93	21.2	63.7	46.8	Wall suction tube
3	Hospital personnel	(i) Breast reduction (ii) Buccal surgery	180 80	VOC: 180[c] PAH: None[d] Badges: 478	326	34.4	2.93	13.6	22.5	9.06	None
4	Hospital personnel	(i) Breast reduction (ii) Panniculectomy	240 200	VOC: 225[c] PAH: None[d] Badges: 470	428	30.9	2.93	12.9	19.1	7.96	Smoke evacuator and wall suction tube[h]
5[e]	Hospital personnel	(i) Penectomy, bib orchiectomy, c-graft	240	VOC: 180[c] PAH: 255[d] Badges: 259	None[g]	36.1	2.93	12.3	21.5	10.3	Wall suction tube
6[e]	Hospital personnel	(i) Left groin flap div and inset, urethroplasty	300	VOC: 196[c] PAH: 194[d] Badges: 197	[21][f]	59.2	2.93	21.2	63.7	46.8	Wall suction tube
7	Background	None	None	VOC: 171 PAH: 399 Badges: 398	None[g]	—	—	—	—	—	—
8	Background	None	None	VOC: 469 PAH: None[d] Badges: 468	None[g]	—	—	—	—	—	—
9	Blank	—	—	—	—	—	—	—	—	—	—

[a] Hospital personnel samples included both discrete personal samples and real-time area samples. For background samples, all discrete and real-time samples were area samples.

[b] All surgeons used electrocautery instruments (Bovie knife).

[c] All canister-based VOC samples, except the sample collected as part of sample set 8, had a duration less than the length of the surgical technicians' shifts. There was either a calibration issue with the flow regulators or a systematic connection seal issue with the canister flow controllers such that they filled the canister in a three to four- hour period rather than in the intended eight-hour period.

[d] The study participants associated with sampling sets 3 and 4 requested that PAH samples not be collected during their work due to the noise generated by the personal sampling pumps. Personal pump failure led to a shortened PAH sample duration for the sample collected as part of set 2, and personal pump failure led to lack of collection of a background sample for PAHs as part of set 8.

[e] All samples in sample sets 5 and 6 were collected for a partial-shift at the request of the study participants. Samples of all types in these two sample sets therefore had a sampling duration of approximately 180 to 260 minutes.

[f] P-TRAK battery failure led to substantially shortened real-time monitoring periods for UFP samples that were part of sets 2 and 6.

[g] UFP and hazardous gases were not measured in background samples in sets 7 and 8 because of lack of operable real-time monitoring equipment. The participant associated with sampling set 5 requested that real-time monitoring devices not be used during the work period.

[h] During breast reduction surgery only.

limits are available in Supplementary Table A.1, available at *Annals of Work Exposures and Health* online.

Aldehydes

Passive dosimeter badges (AssayTech 571A; Assay Technology, Inc., Livermore, CA, USA) were used to monitor 10 individual aldehydes: acetaldehyde, benzaldehyde, butyraldehyde, crotonaldehyde, formaldehyde, glutaraldehyde, hexanal, *m*-tolualdehyde, propionaldehyde, and valeraldehyde. The passive dosimeter badges contained a sampling medium of 2,4-dinitrophenylhydrazine-coated fiberglass. Samples were analyzed using modified OSHA 64 (glutaraldehyde) and modified United States Occupational Safety and Health Administration (OSHA) 1007/EPA TO-11 methods (all other aldehydes; Assay Technology, Inc.). Briefly, the sampling media was removed from the badges and desorbed in acetonitrile and neutralized using a buffer. Each aldehyde's 2,4-dinitrophenylhydrazine derivative was analyzed using high-performance liquid chromatography (HPLC) equipped with an ultraviolet/visible (UV/VIS) detector.

Phenol

Phenol monitoring was performed using passive air sampling badges (AssayTech 521; Assay Technology, Inc.). The passive air sampling badges contained a sampling medium of 365 mg activated carbon with a polytetrafluoroethylene (PTFE) binder. Samples were analyzed using a modified OSHA 32 method using carbon media, and a 15% carbon disulfide, 85% methanol desorption solution (Assay Technology, Inc.).

Volatile organic compounds

Seventy-five individual VOCs were monitored using Summa canisters (full list available in Supplementary Table A.1 available at *Annals of Work Exposures and Health* online). Samples were analyzed using EPA TO-15 (ALS Environmental, Simi Valley, CA, USA) to achieve sub-ppb level detection limits. In this method, whole air samples collected in passivated canisters are analyzed for individual VOC content using gas chromatography/mass spectrometry (GC/MS). VOC monitoring was performed using evacuated 1.0-L Summa canisters with critical orifice flow controllers calibrated to allow constant airflow into the 1.0-L container over a period of 8-h.

Polycyclic aromatic hydrocarbons

Filter and sorbent tube sampling was performed to monitor 16 individual PAHs: acenaphthene, acenaphthylene, anthracene, benz(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(g,h,i)perylene, benzo(k)fluoranthene, chrysene, dibenz(a,h)anthracene, fluoranthene, fluorene, indeno(1,2,3-cd)pyrene, naphthalene, phenanthrene, and pyrene. Sampling for PAHs was conducted in accordance with NIOSH Method 5506. The sampling train included a 37-mm diameter PTFE filter with 2.0 µm pore size and a washed 100 mg/50 mg XAD-2 tube attached to the pump via vinyl tubing. Samples were collected using Gilian GilAir-5 personal sampling pumps (Sensidyne, LP; St. Petersburg, FL, USA). The sampling pumps equipped with the full sampling trains were calibrated before and after collecting each sample (BIOS DryCal Defender 510; Prairieville, LA, USA). The sampling flow rate for each pump was ~2.0 L min^{-1}. Samples were analyzed using NIOSH 5506 (RJ Lee Group, Inc.; Monroeville, PA, USA). In this method, the PAH sampling media is extracted using acetonitrile and analyzed using HPLC with fluorescence/ultraviolet detection.

Area air sampling

Area sampling instruments were placed on a cart in the surgical suites at a height of ~1.1 m (3.5 ft). Circulating nurses ensured that the cart was placed as close as possible to the surgical technician's primary work station. The cart was located ~0.9 to 2.4 m (3 ft to 8 ft) from ongoing surgical procedures at various times, according to physical space needs of the surgical teams.

Ultrafine particulate

Real-time monitoring for UFP was performed using Model 8525 P-TRAK® Ultrafine Particle Counter (P-TRAK) devices (TSI, Inc.; Shoreview, MN, USA). P-TRAK devices use a laser-based photodetector system to detect airborne particulate matter in the size range of 0.02–1 µm. The devices measure particulate matter in this size range between concentrations of 0 and 5 × 10^5 particles/cm^3 and have an analytical sensitivity of ~1 particle/cm^3. All devices were set to record one 60-s average particle concentration per minute.

Hazardous gases (carbon monoxide, hydrogen cyanide, hydrogen sulfide)

Real-time monitoring was used to assess hazardous gas concentrations in the surgical suite. Three hazardous gases of interest were monitored: carbon monoxide (CO), hydrogen cyanide (HCN), and hydrogen sulfide (H_2S). RKI GX-6000 devices were used to perform real-time monitoring (RKI Instruments; Union City, CA, USA). RKI GX-6000 devices use electrochemical sensors to detect the three gases monitored in this study. The detection range, sensitivity, and accuracy for CO were 0–500 ppm, 1 ppm, and ±5% of the reading or ± 5 ppm (whichever is greater), respectively. The detection range, sensitivity, and accuracy for HCN were

0–15 ppm, 0.1 ppm, and ±10% of the reading, respectively. The detection range, sensitivity, and accuracy for H_2S were 0–100 ppm, 0.5 ppm, and ±5% of the reading or ± 2 ppm (whichever is greater), respectively. All devices were set to record gas concentrations six times per minute (one reading per 10 s).

Field observations

Observations of local exhaust ventilation via open suction tubes or smoke evacuators were made, but no quantitative measurements of airflow rate or air velocities generated by local exhaust ventilation equipment were collected. Other data were recorded during the sampling: location of the technician with respect to the surgeon; proximity of the technician to the ongoing procedure; type of gown; and personal protective equipment use.

Results

Personal air sampling

A total of 17 analytes were detected at least once during the sampling campaign (Table 3). α-pinene, benzene, methylene chloride, and *n*-hexane were detected in personal samples but were not detected in either of the background samples. The geometric means of the remaining analyte concentrations were within a factor of two of the background concentration, with the exception of ethanol and ethyl acetate, which had geometric mean concentrations 3.7-fold and 2.4-fold greater than the background concentration, respectively. Comprehensive personal sampling results are available in Supplementary Table A.2 (available at *Annals of Work Exposures and Health* online).

Area air sampling

UFP concentrations were acquired for sample sets 1, 3, and 4 and exhibited appreciable inter- and intra-procedure temporal variability (Fig. 1). Short-term (1- or 15-min) maximum concentrations were generally an order of magnitude greater than the full-shift concentrations, which ranged from 773 to 2257 particles/cm^3 (Table 4).

Detectable concentrations of CO of 1 ppm (as 10 s averages) were observed in sampling set 4 for a cumulative period of 32.3 min, with a maximum 15-min average of 0.3 ppm. CO, HCN, and H_2S (as 10-s averages) were not detected in any other surgical suite during any other monitoring period.

Field observations

All surgical technicians donned a Medline Protection Level 4 Gown for each procedure. The employees associated

Table 3. Results for analytes detected in personal and area samples.

Analyte[a]	Detection Percentage	Geometric Mean (GM) Concentration (ppm)	Geometric Standard Deviation	Ratio Between GM and Measured Background	Ratio Between GM and Method Reporting Limit	Average Sampling Duration (min)
2-Propanol	83	0.17	3.0	0.75	7.2	185
Acetone	100	0.015	1.4	1.4	2.0	187
alpha-Pinene	33	0.00039	1.3	*NBD*[b]	1.2	203
Benzene	17	0.0011	—	*NBD*[b]	1.9	180
Dichlorodifluoromethane	100	0.00047	1.0	0.98	1.3	187
D-Limonene	50	0.00050	1.5	1.1	1.5	195
Ethanol	100	3.0	3.5	3.7	27	187
Ethyl acetate	33	0.0036	1.3	2.4	3.5	180
Ethylbenzene	50	0.00069	1.2	0.57	1.6	195
Fluorene	75	0.00016	1.5	1.6	1.4	340
m,*p*-Xylenes	33	0.0011	1.1	0.57	1.4	203
Methylene chloride	17	0.00060	—	*NBD*[b]	1.1	180
n-Butyl acetate	33	0.00072	1.5	0.65	1.9	203
n-Hexane	33	0.0026	1.5	*NBD*[b]	5.1	188
o-Xylene	33	0.00056	1.2	0.70	1.3	203
Propene	100	0.015	2.8	0.68	14	187
Toluene	83	0.0013	2.3	0.56	2.8	185

[a]$n = 6$ and $n = 2$ samples were collected for all samples except PAHs, for which $n = 4$ personal samples and $n = 1$ background samples were collected.
[b]No background concentrations detected.

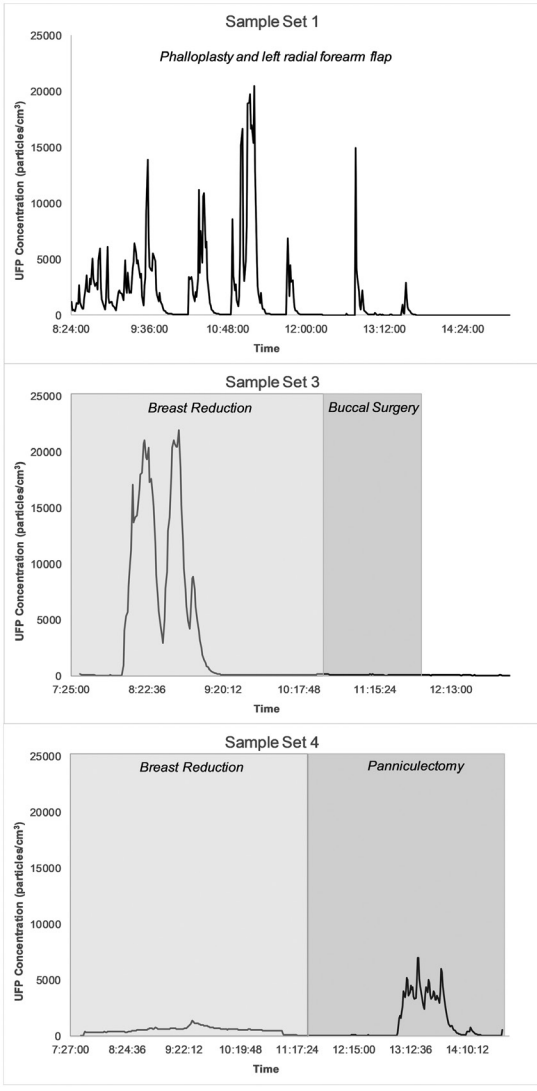

Figure 1. Time pattern of UFP concentration for real-time area samples. For sample set 3, the average UFP concentration and number of peaks were much larger in the morning period than in the afternoon period because of less use of electrocautery devices in the afternoon procedure. For sample set 4, we observed that both the average UFP concentration and number of peaks were much larger in the afternoon period than in the morning period because of the use of a smoke evacuator during the morning procedure.

with sample sets 1 and 6 wore a Halyard Model 49125 surgical mask, whereas those associated with sample sets 2 and 3 wore a Halyard Model 47500 surgical mask, the employee associated with sample set 4 wore a Kimberly-Clark N95 Model 46767 surgical mask, and the employee associated with sample set 5 wore a Halyard Fog-Free Fluid Resistant Mask Type 11R surgical mask.

The employee associated with sample set 1 was always observed to be within ~ ≤0.3 m (≤ 1 ft) of ongoing surgical activity, whereas the employee associated with sample set 2 was ~0.6 to 0.9 m (2–3 ft) from surgical activity and those associated with sample sets 3, 4, 5, and 6 were ~0.9 m (3 ft) from surgical activity.

Ventilation information for the operating rooms and scrub rooms was obtained from the hospital engineering department. Local exhaust ventilation (wall suction) was used in all but one surgical procedure, and one surgeon used a smoke evacuator in addition to wall suction during a breast reduction procedure. Each surgical suite had different airflow and ventilation rates (Table 2).

Discussion

We investigated the potential presence of 106 different analytes (102 personal, 4 area) during surgical procedures involving the use of electrocautery instruments. Including background samples, the most prominent and consistently measured analytes were 2-propanol, acetone, dichlorodifluoromethane, ethanol, fluorene, propene, and toluene. Detection of 2-propanol, acetone, and ethanol in air samples was not surprising because these substances are commonly used for cleaning and sterilizing hospital equipment. Regardless of the source, all detected substances were measured at concentrations <1% of the corresponding 8-h OSHA permissible exposure limits (PELs) or 8-h California OSHA (Cal/OSHA) PELs. All other compounds were non-detectable at reporting limits far smaller in magnitude than their corresponding PELs. No OSHA or Cal/OSHA PELs exist specifically for UFP.

Of the studies described in Table 1, many involved sampling within a few centimeters of the emission source, and multiple others involved capture and measurement of emissions in a sealed chamber. Airborne

Table 4. Summary results for UFP using real-time area monitoring.

Sample Set Identifier	Full-Shift Average UFP Concentration (particles/cm³)	15-min Maximum UFP Concentration (particles/cm³)	1-min Maximum UFP Concentration (particles/cm³)	Total Duration of Area UFP Sampling (min)
1	1573	13 226	20 476	403
3	2257	17 554	21 951	326
4	773	4643	7011	428

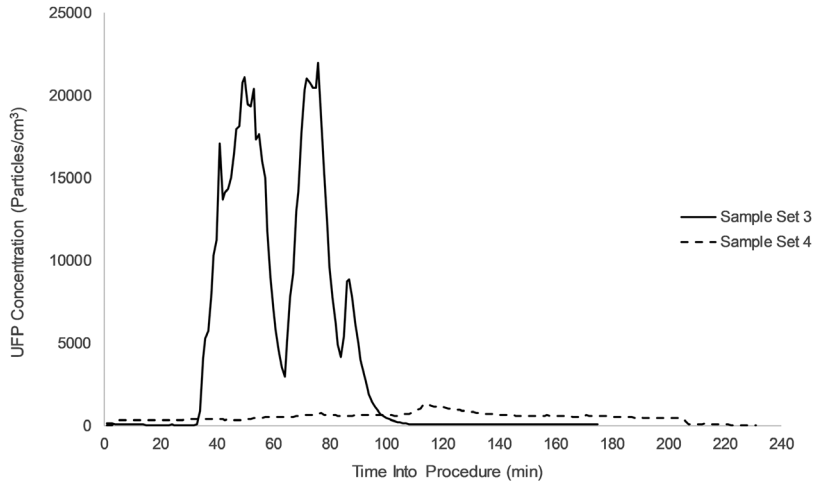

Figure 2. Comparison of measured UFP concentrations during two breast reduction surgeries with use of a smoke evacuator (sample set 4) and without use of a smoke evacuator (sample set 3). A substantial difference in UFP concentrations was observed between the two breast reduction surgeries.

concentrations in occupational settings generally decrease with distance from the source due to turbulent dispersion and clearance by exhaust ventilation (Nicas, 2009). Particulate source concentrations are subject to additional attenuation due to gravitational settling and surface impaction. Thus, we focus our subsequent comparisons on investigations in which personal and area sampling techniques representative of breathing zone positions were used during live surgeries.

Assessment of UFP concentrations

The local maxima and peaks in UFP concentration corresponded to periods involving use of electrocautery devices based on qualitative field observations (Fig. 1). It is possible that the increased ventilation rate in the hospital rooms for sample set 1 (24.8 h^{-1}) compared to the ventilation rate in the hospital rooms for sample sets 3 and 4 (13.6 and 12.9 h^{-1} air exchange rates, respectively) resulted in a more rapid decrease in measured particle concentrations after peaks occurred. The average UFP concentration and number of peaks for sample set 3 were much greater in the morning breast reduction when compared to the afternoon buccal surgery, consistent with the difference in the duration of electrocautery instrument use. In contrast, differences in sample set 4 were possibly attributed to the use of a smoke evacuator in the morning breast reduction, but not the afternoon panniculectomy (rather than differences in instrument usage). We observed an ~ 8-fold difference in mean UFP concentrations between the two breast reduction surgeries with (529 particles/cm^3 averaged over 3 h; sample set 4) and without a smoke evacuator (4139 particles/cm^3 averaged over 4 h, sample set 3; Fig. 2). Although using the smoke evacuator appeared to have made an appreciable reduction in UFP concentrations, other factors may have also contributed to the observations. Specifically, the first breast reduction surgery was conducted without using either the smoke evacuator or wall suction, and the second breast reduction surgery used both wall suction and smoke evacuation. In addition, differences in usage of electrocautery instruments (e.g. usage time, instrument settings, and surgical technique), distance from sampling equipment to surgical site, and general ventilation may have also contributed to the concentration differences (Lee et al., 2018).

Study result comparisons

An approximate order of magnitude full-shift increase above background surgical suite UFP concentration (100 particles/cm^3) was generally observed during electrocautery device use (Table 4; Figs. 1 and 2). The background UFP concentrations were consistent with background UFP levels measured in clean indoor environments and other inactive surgical suites (Brüske-Hohlfeld et al., 2008; Meda, 2013; King, 2014; Bo et al., 2017).

Mean UFP concentrations between 1260 and 12 200 particles/cm^3 have been measured in the breathing zones of anesthetists using a real-time particle counter with a suction tube attached Brüske-Hohlfeld et al., 2008). Sample durations ranged between 73 and 193 min during single surgeries, including adhesiolysis/tumor removals, hemihepatectomy, hernia repair, biliodigestive anastomosis, and laparoscopic appendectomy. The lower

bound of the average values are similar in magnitude to full-shift concentrations found in our study, and the upper bound is similar to our 15-min maximum UFP concentrations. Although we were unable to estimate 15-min averages for the Brüske-Hohlfeld et al. (2008) study, the large standard deviations (3540–43 100 particles/cm^3 for samples with mean values <1000 particles/cm^3) suggest that 15-min averages were somewhat higher than in our study. Differences in type of surgery, different electrosurgical devices, different device settings, and varying surgical technique likely contributed to the differences between our observations and this study.

Interpreting UFP concentrations

Anecdotal evidence regarding indoor air quality suggests that increases in UFP above typical surgical suite background concentrations are related to complaint areas and that eliminating UFP sources can reduce subjective symptoms, such as reports of eye and respiratory irritation (Keady and Halvorsen, 2000; Nur Fadilah and Juliana, 2012). However, specific regulatory limits or guidelines for UFP have not been derived for occupational environments, and few studies have assessed objective short-term human thresholds of adverse respiratory effects for specific occupational sources of UFP (Viitanen et al., 2017; Jordakieva et al., 2018). The UFP concentrations measured in our study should be interpreted within the context of the magnitude of the transient elevations observed over baseline surgical suite concentrations, which could potentially contribute to perceptions of poor air quality in the surgical suite by workers within.

Assessment of VOCs

The first NIOSH surgical suite evaluation involving VOC's was conducted in the 1980s and found that the benzene-soluble fraction on 7 of 11 particulate matter samples exceeded the NIOSH recommended exposure limit (Bryant et al., 1988). Subsequent NIOSH evaluations conducted in the 2000s considered VOCs, PAHs, aldehydes, CO, cresols, phenol, and HCN. These evaluations reflect improvements in surgical suite engineering controls and electrocautery instrument designs. The detected constituents across studies included formaldehyde, acetaldehyde, and toluene, with a range in detection limits of non-detect to 21 ppb, non-detect to 14 ppb, and 2–720 ppb, respectively. The highest concentrations were consistently observed in samples collected on the surgeon or surgeon's assistant. NIOSH did not evaluate employees for the entire work shift but noted that time-weighted average exposures of detected VOCs would not have exceeded occupational exposure limits similar to the analysis we present in our study. General room ventilation and local exhaust ventilation was recommended in all four NIOSH HHEs (Bryant et al., 1988; King and McCullough, 2006a,b,c).

Results for VOCs collected in the area around a surgeon's headlamp during laparotomy procedures for abdominal surgeries are available; however, no description of the surgical suite or the sampling durations were provided (Moot et al., 2007). Several analytes were detected and quantified: HCN (21–91 ppb), acetylene (2–40 ppb), 1,3-butadiene (0–2 ppb), furfural (10–21 ppb), 1-decene (7–17 ppb), and propanenitrile (6–12 ppb). Of these analytes, only 1,3-butadiene and HCN were included in this study, and neither were detected in any sample (Moot et al., 2007). In our study, the HCN monitor was too cumbersome to be worn by the surgical technicians and may have been placed too far from the surgical field to serve as a surrogate for personal exposures. Alternatively, instrument sensitivity (100 ppb in our study) or differences in air exchange rates (not reported by Moot et al.) could potentially explain the differing study outcomes.

Assessment of PAHs

PAH concentrations in electrocautery smoke generated during 50 abdominal surgeries at a fixed point ~7 cm from the operative field have been investigated (Claudio et al., 2017). On average, the surgeries lasted 136 min and monopolar electrocautery was used for an average of 3.6 min per procedure. Only two PAHs were detected during surgical events: naphthalene (range 0.0004–0.0188 mg m^{-3}) and phenanthrene (range 0.0001–0.0031 mg m^{-3}); neither naphthalene nor phenanthrene were detected in our study. One possible explanation for the observed differences in PAH concentrations between the abdominal surgery investigation and this study is that the ventilation in the study conducted by Claudio et al. (2017) was limited to air exchange that can be achieved naturally via two open doors and two air conditioning units per room.

Strengths and limitations

To our knowledge, this study is one of the first to characterize surgical suite employee exposures to a panel of chemical and particulate agents during the use of electrocautery devices for live human surgeries. In addition, the sampling and analytical methods used in this study provided detection limits well below current occupational exposure limits, which is important if further research is performed on the interactions of individual chemical

agents measured here to understand the health risks of exposures to mixtures, rather than to isolated substances. Finally, new data regarding potential airborne chemical exposures and UFP concentrations as a function of time during electrocautery procedures were obtained. These data expand the existing field of knowledge of particulate exposure in the surgical suite due to electrocautery smoke.

The limitations of our study are primarily associated with the small sample size constrained by the resources available for this research and by sampling equipment deficiencies or operational failures. Our design did not allow for development of a statistically robust understanding of the impact of different exposure parameters, such as the various types of surgical procedures, length of surgeries, ventilation parameters, or the distance of the surgical technician from the surgeon. In addition, the unique setting of a surgical suite presented conditions that do not typically hinder an industrial hygiene evaluation and we address consideration of these conditions in our recommendations later. Finally, our selection of area real-time monitors for measurement of UFP and hazardous gas concentrations (compared to a personal sampling technique) may have resulted in underestimation of the true breathing-zone concentration of these analytes (Rodes et al., 1991).

Recommendations

The current electrocautery industrial hygiene literature is heterogeneous with respect to instrumentation used, types of surgeries performed, conditions within the operating room, tissues impacted, and analytical methods used. Thus, we have developed recommendations for future surgical suite surveys and research based on the findings of our pilot study.

Considerations for surgical suite surveys

We concluded that sampling plans involving the operating theatre should be carefully coordinated with the surgical team before mobilization. The noise generated by the personal sampling pumps proved to be aggravating/distracting, such that they were ultimately rejected by one surgical team. The high-risk circumstances of the surgical procedures and patient privacy concerns prohibited interruption of the work activities by the industrial hygienists to check on sampling devices or correct sampling device failures when they occurred. The isolated environment also prevented investigators from directly observing personnel as they performed tasks. Limited access to the work area is a key consideration for industrial hygienists performing work in surgical suites, and, consequently, passive badge sampling methods with appropriate limits of detection may be the best option for ensuring limited sample loss. We recommend placing sampling equipment on the surgeon, the surgeon's assistant and the circulating nurse as this would be beneficial in determining a complete exposure profile for all exposure groups. However, this approach can be challenging because some instrumentation may require surgical team members to remain stationary during the sampling period (Ragde et al., 2016).

We found an approximate one order of magnitude increase in UFP concentration during electrocautery instrument use, which, when paired with the potential for a visible plume, could contribute to perceptions of impacts to air quality in the surgical suite. Particulate matter of all types may cause eye, throat, and respiratory irritation at sufficient air concentrations. The irritation threshold of various types of particulate matter depends on the chemical composition and size distribution. UFP, with a size range <100 nm, is thought to have a higher pathogenic potency for respiratory and cardiovascular issues due to high specific surface area, high oxidation potential, and high deposition efficiency in the pulmonary region compared to larger particulate matter (Soppa et al., 2014). Electrocautery procedures generate particles on the order of 70 nm in size (Benson et al. 2013). Thus, minimizing exposure to particulate matter is strongly recommended. NIOSH has recommended proper dilution ventilation, as well as local exhaust ventilation via smoke evacuators (NIOSH, 1996). We recommend the use of N95 respirators over standard surgical masks. Previous research has demonstrated that surgical masks provide limited UFP protection because they do not seal to the face (Benson et al., 2013). Air-purifying respirators provide adequate protection, and a properly fitting N95 respirator consistently prevents at least 95% of UFP from penetrating the filter media (Shaffer and Rengasamy, 2009; Gao et al., 2016). A simulated workplace protection factor study demonstrated that surgical N95 respirators significantly decreased exposures to surgical smoke, including UFP measured on the order of 10 nm to 1 μm with a distributional peak at 60–150 nm (Elmashae et al., 2018). As such, we recommend the use of surgical N95 respirators as a hospital best practice and encouraging their use through effective communications with nurses and surgeons.

Future research

On the basis of our review of the literature and pilot study findings, we concluded that future research protocols should focus on the selection of sampling methods for key health hazards and evaluate concentration results using those methods under a variety of experimental conditions where only one influencing factor is changed at a time. Additional data collected in individuals' breathing zones

would help to fill key data gaps regarding distance to source and exposures. Measurements of the tissues being cut and volume or mass of tissue being removed would be helpful for characterization of the generation rates of contaminants. The air concentrations of surgical smoke components are directly related to the amount of surgical smoke (or surgical plume) produced, the duration of the overall procedure, and the overall potential inhalation exposure to surgical smoke plume components. Finally, this study did not address the potential biological viability of the particulate matter present in surgical smoke. Future research would benefit from focusing on either qualitative assessments of, or quantitation of, the potential biological activity of particulate matter generated by electrocautery instruments during live surgeries.

Conclusions

Other than UFP, no analyte was identified in substantial excess of background concentrations and no analyte with a federal or state PEL was detected at concentrations of concern with respect to the existing PEL. We conclude that UFP generation studies, further quantification of airborne concentrations of hazards, and studies regarding the biological activity, would benefit the community's understanding of the potential health effects of surgical smoke. In addition, key hazards such as UFP should be identified and assessed under a variety of experimental conditions to provide further insight as to the causes of potential health effects and causes of employee complaints.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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