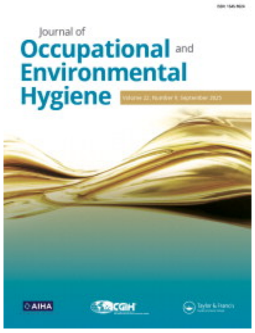

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Evaluation of a smoke extraction system for veterinarian exposures to surgical smoke—A pilot study

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ABSTRACT
Electrosurgery generates surgical smoke, which contains hazardous compounds. The concentration, composition, and size distribution of surgical smoke vary significantly with surgery type, duration, and number of times electrocautery is used. Exposure assessments have focused on characterizing occupational exposure to surgical smoke during human surgeries, but occupational exposure to surgical smoke during veterinary surgeries is largely unknown. Given the hazardous exposure concentrations identified in human surgical procedures, similar occupational exposures are expected in small animal surgeries. Thus, there is a critical need to evaluate occupational exposures among veterinarians conducting small animal surgeries and to evaluate potential exposure reduction systems. The objectives of the study are to quantify the particle number concentration and size distribution during canine limb amputation (CLA) surgery and to quantify the exposure reductions associated with a smoke evacuation system (SES). Exposure to ultrafine particles (UFP) during CLA was measured using a TSI NanoScan Scanning Mobility Particle Sizer (SMPS) Nanoparticle Sizer 3910 during surgeries with and without the SES. Particle number concentrations were 11 times higher compared to background concentrations during CLA surgeries. The particle number concentration was significantly reduced when using SES during surgery compared to surgeries without SES. The average total particle number concentration near the veterinarian's breathing zone was 25,141 particles/cm^3 for surgeries without SES and 7,643 particles/cm^3 when the SES was used during surgeries, which represents about a 70% reduction in exposure. CLA was associated with particle exposures similar to those seen in human surgeries. The use of SES effectively reduced the concentration of particles near the surgeon's breathing zone.

KEYWORDS
Amputation; electrosurgery; engineering controls; exhaust ventilation; ventilation; veterinary medicine

Introduction

Electrosurgery is a technique of applying thermal energy produced by high-frequency, alternating electric current to tissues in surgeries to coagulate blood, decrease bleeding, and improve the field of view (Hassan et al. 2006). Thermal energy is generated at the tip of a pen-like tool and applied to surfaces to cut or coagulate tissues. This application of high temperatures to tissues generates smoke. Surgical smoke generated from electrosurgery contains both hazardous gaseous and particulate compounds that are associated with cancer and respiratory irritation. Several factors can account for the variety of concentrations reported in surgical smoke. Concentration, aerosol size, and composition of surgical smoke vary depending on tissue type, procedure, patient body mass index, duration of the surgery, and energy of the electrosurgery use (Karjalainen et al. 2018; Ragde et al. 2016).

Studies have shown that high aerosol concentrations are produced during electrocautery use in surgeries (Andréasson et al. 2009; González-Bayón et al. 2006; Heinsohn and Jewett 1993). Brüske-Hohlfeld et al. (2008) reported very high UFP concentrations ($>1 \times 10^5$ particles/cm^3 or #/cm^3), although concentrations varied based on the type of surgery and only one measurement was made for each surgical procedure. Ragde et al. (2016) also evaluated UFP generation during five different types of surgeries and reported substantial short-term peak exposures with number

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concentrations up to 2.72×10^5 #/cm^3. The size of particles generated during surgery varied substantially by type of surgery. The smallest particle sizes were generated during nephrectomy and hip replacement surgeries, whereas larger particle sizes were generated during breast reduction surgery and abdominoplasty. Surgery type was the strongest predictor of both overall concentration levels and the size distribution. Given the complex contaminant mixtures generated during electrocautery use and the high variability in concentration and size distribution between surgery types, further evaluation of the potential occupational exposures is warranted.

While surgeons wear surgical masks in the operating theater, surgical masks are not designed to protect surgeons from occupational smoke exposures (Gao et al. 2016). Several regulatory bodies including the American Nurses Association, Association of periOperative Registered Nurses (AORN), American National Standards Institute (ANSI), National Institute for Occupational Safety and Health (NIOSH), Joint Commission, and the Occupational Safety and Health Administration (OSHA) have made recommendations for implementations of controls to prevent exposure to surgical smoke (AORN 2017; Born and Ivey 2014; Okoshi et al. 2015). Among these recommendations is the use of high filtration masks, which filter particles as small as 0.1 µm. However, filtration levels of masks vary based on the manufacturer, and engineering controls should also be present to evacuate surgical smoke.

Smoke evacuation systems (SES) are one control option used to capture the surgical smoke plume at the tip of the electrocautery pen. However, the efficiency of these systems varies, and manufacturers rarely report performance data for these units. Schultz (2014) summarized several smoke evacuation system types and reported capture efficiencies for different systems ranged from 51 to 99.5%. Schultz (2014) also noted several factors that affect the efficiency of SES, including suction flow rates, capture velocities, location of the system to the source, and overall smoke concentrations.

Although there is a large and growing body of literature surrounding occupational exposures in human surgeries (Barrett and Garber 2003; Benaim and Jaspers 2024; Bigony 2007; Bree et al. 2017; Merajikhah et al. 2022; Ulmer 2008), occupational exposure to surgical smoke in veterinarians conducting electrosurgery is largely unknown. Several studies have examined the chemical composition of human surgical smoke (Barrett and Garber 2003; Bigony 2007; Bree et al. 2017; Hassan et al. 2006; Hensman et al. 1998; In et al. 2015; Karjalainen et al. 2018; Kocher et al. 2019; Näslund Andréasson et al. 2012; Nicholas et al. 2013; Okoshi et al. 2015; Sagar et al. 1996; Tramontini et al. 2016; Ulmer 2008). High levels of polycyclic aromatic hydrocarbons (PAHs) have been reported in mastectomy, peritonectomy, laparoscopic digestive tract surgeries, with naphthalene being reported as the most abundant compound (Fitzgerald et al. 2012; Gianella et al. 2014; Näslund Andréasson et al. 2012; Tseng et al. 2014). Exposure to PAHs can cause cancer and adverse skin, liver, and immune system responses. Volatile organic compounds (VOCs) have also been reported in human surgical smoke, with high concentrations of benzene, isobutylene, toluene, and 1,3-butadiene (Al Sahaf et al. 2007; Choi et al. 2014; Chung et al. 2010; Fitzgerald et al. 2012; Hollmann et al. 2004; Lin et al. 2010; Moot et al. 2007; Park et al. 2012; Weston et al. 2009; Wu et al. 2011; Zhao et al. 2013). Benzene is classified as a carcinogen, toluene can cause adverse cardiovascular and nervous system effects, and 1,3-butadiene can cause central nervous system effects and has been classified as carcinogenic. Several factors account for the variety of chemicals present in surgical smoke. Concentration, aerosol size, and composition of surgical smoke vary depending on tissue type, procedure, patient's body mass index, duration of the surgery, and energy of the electrosurgery used (Karjalainen et al. 2018; Ragde et al. 2016). Patients may also have been treated with drugs that could alter the chemical composition of surgical smoke. Given the high variability in contaminant composition and concentrations in human surgical smoke, it stands to reason that similar complexities exist in veterinarian surgical exposures. Studies in human surgeries described that the chemicals found in surgical smoke have been shown to induce acute and chronic inflammatory changes in the respiratory tract, including those leading to upper respiratory tract irritation, rhinitis, asthma, and bronchiolitis and emphysematous changes consistent with chronic obstructive pulmonary disease (COPD) (Alp et al. 2006; Ilce et al. 2017; National Institute for Occupational Safety and Health 1996; Okoshi et al. 2015; Ulmer 2008; Xie et al. 2021). A study of perioperative (human medicine) nurses found that the prevalence of reported respiratory problems was twice that of the general population (Ball 2010), and analyses of data from the U.S. Nurses' Health Study found operating room (OR) nurses were at a higher risk of severe persistent asthma compared with administrative nursing

(Le Moual et al. 2013). While there is mounting evidence that surgical smoke during human surgeries poses health risks, there is limited literature regarding surgical smoke generated during veterinary surgeries. Veterinary surgeons perform a variety of surgical procedures, including orthopedic, soft tissue, oncologic, and neurological surgeries. Electrosurgery is often used, especially for oncologic surgery, which has evolved significantly in the past 10 years. Careful control of bleeding is essential in cancer surgery, especially when removing large tumors or performing limb amputations. Resection of large muscles during limb amputation generates substantial levels of smoke in the operating room. Because the number of electrosurgeries has significantly increased in veterinary medicine, questions have been raised regarding the exposure of surgery staff to surgical smoke. Thus, there is a critical need to evaluate occupational exposures among veterinarians conducting small animal surgeries.

The objectives of this pilot study were to conduct an exposure assessment to characterize the magnitude and variability of airborne particle concentrations and to evaluate the performance of an SES in reducing particle concentrations in worker breathing zones at the University of Minnesota Veterinary Teaching Hospital.

Methods

All trials were conducted at the University of Minnesota Veterinary Medical Center, which consists of six surgical suites. Over 40 staff members, including board-certified veterinary surgeons and anesthesiologists, small animal residents, rotating interns, veterinary technicians, and senior veterinary students, work in the operating theater and conduct an estimated 1,500 small animal surgeries a year. Particle exposures were evaluated during canine limb amputations in a closed, single-unit surgical suite (one surgery bed). The pilot study was conducted prospectively with a waiver of institutional animal care and use committee review by the University of Minnesota Animal Care Board. The criteria for case enrollment were limb amputation surgeries for canine bone tumors in a clinical patient with a body weight of 20–50 kg. A routine forelimb or coxofemoral disarticulation amputation was performed by either an American College of Veterinary Surgeons (ACVS) diplomate or resident under the supervision of an ACVS diplomate. All surgeries were conducted in a closed surgery room ($32.5\ m^2$) with a laminar airflow system with an air exchange rate of 20 air changes per hour.

Surgical smoke was generated by electrocautery using a Bovie electrosurgical push button pencil (Symmetry Surgical, Antioch, TN) during surgeries without a SES or a PlumePen Pro (CONMED, Largo, FL) for surgeries with the local exhaust ventilation capabilities. Electrocautery pens were set to coagulation mode with output power between 20 and 25 watts (DRE electrosurgical unit ASG-300, Avante, Louisville, KY). The smoke evacuation system (VisiClear, CONMED, Largo, FL) used in this study was a unit with the suction port surrounding the electrode tip approximately 1 inch above the tip. The suction shroud is connected to a pump that evacuates the smoke through a filter with >99.9% efficiency for particles 0.1 to 0.2 µm in diameter. The pump was set to the highest flow rate of 30 cubic feet per minute (cfm), which was automatically activated (EZLink, CONMED, Largo, FL) when electrocautery instrumentation was used. Six trials were conducted without a smoke evacuation system (the clinic's baseline), and six trials were conducted with the smoke evacuation system.

Total number and size-distribution measurements were made using a TSI Nanoscan (TSI Inc., Shoreview, MN) and TSI Condensation Particle Counter (CPC, TSI Inc., Shoreview, MN). The Nanoscan scanning mobility particle sizer measured particles in the size range of 10 to 420 nm in diameter across eight size bins at a one-minute sampling resolution. Total particle number concentration, which is the sum of particles across all sizes measured, was also reported. The CPC measures total particle number concentration for particles 0.01 to 1 µm in diameter. The data output was expressed as total number of particles per cubic centimeter of air ($\#/cm^3$) with an upper dynamic range limit of approximately $1 \times 10^6\ \#/cm^3$ for the Nanoscan and $1 \times 10^5\ \#/cm^3$ for the CPC. Exposure monitoring was conducted for the entire duration of the surgeries, which ranged from 2 to 4 hr. Samplers were placed directly underneath the surgical bed and Tygon tubing was run up the bed with inlets located on a tray by the surgical instruments near the surgeons' breathing zone, so as not to impede animal care (Figure 1). Tubing was less than 3 feet long, and calculated particle losses ranged from 14% for 10 nm particles and less than 1% for 100 nm particles. While this is not a true personal exposure measurement, this allowed for exposure monitoring near the breathing zone while still accounting for the workflow requirements of the surgeons. Background concentrations were established by measuring particle concentrations for 5 min before the start of each surgery.

All statistical analyses were performed in R (version 4.3.3, RStudio, PBD). Descriptive statistics, including mean, median, 25th and 75th percentiles, and maximum total particle number concentration, were computed for surgeries with and without the SES for both the Nanoscan and CPC. Data were non-normally distributed; thus, differences in the total concentrations and size-distribution measurements were compared for surgeries with and without SES using the Kruskal-Wallis (Wilcoxon rank sum) test. Collection efficiency as a function of particle size was computed using Equation 1:

$$Collection\ efficiency, CE(d_i) = 1 - \frac{\eta(d_i)_{ON}}{\eta(d_i)_{OFF}} \quad (1)$$

where $\eta(d_i)_{ON}$ is the size-distribution function measured while the SES is operating, and $\eta(d_i)_{OFF}$ is the size-distribution function measured without the SES.

Results

Number concentration

Table 1 displays background concentrations and the average total particle number concentrations measured during surgeries with and without SES operating for both the Nanscan and CPC. The Nanoscan failed for one trial without the SES, resulting in a $N = 5$. Due to COVID-19, additional trials were unable to be collected. Background particle number concentrations ranged from 1.5×10^3 to 2.4×10^3 #/cm^3. Average total particle number concentration from the Nanoscan during surgeries without SES usage was 2.6×10^4 #/cm^3, 11 times higher compared to the background concentration of 2.4×10^3 #/cm^3. When the SES was used, mean total particle number concentration from the Nanoscan was 7.8×10^3 #/cm^3, which was 4 times higher than the background concentration of 1.9×10^3 #/cm^3. Operating with an SES resulted in a 70% reduction in exposure (p-value <0.01, Kruskal-Wallis Rank Sum test) near the surgeon's breathing zone.

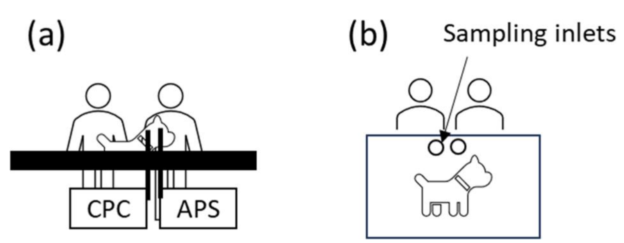

Figure 1. Side (a) and top-down (b) view of the sampling setup in the surgical suite. The sampling instruments were located directly underneath the surgical table, and tubing ran up the side and located between the surgeons and canine as close as practicable to the surgeon's breathing zone.

Total number concentration measured using the CPC during surgeries with and without SES was 4×10^3 and 6.3×10^3 #/cm^3, respectively. Figure 2 shows the timeseries data from the Nanoscan and CPC with and without SES present. Peak concentrations measured with the Nanoscan were substantially higher compared to the CPC. When using the CPC to measure particle number concentrations, operating with an SES resulted in a 36% reduction in particle number concentrations near the breathing zone.

The Nanoscan and CPC differ in terms of minimal detectable particle size and particle concentration range, which may contribute to differences in measured total particle number concentration between the two instruments. Stabile et al. (2014) conducted a metrological assessment of Nanoscan SMPS (model 3910, TSI, Shoreview, MN, USA) and compared its performance to laboratory SMPS spectrometers 3936 (TSI Inc., Shoreview) and a butanol-based CPC 3775 (TSI Inc., Shoreview, MN, USA). They evaluated several exposure scenarios, including testing in a Marple chamber to measure dioctyl phthalate (DOP) particles and diesel particulate matter (DPM), and microenvironment tests to measure different indoor and outdoor aerosols. During cooking tests (the exposure scenario closest to the surgical smoke exposure), the Nanoscan overestimated particle concentration compared to the

Table 1. Descriptive summary statistics of measured particle number concentrations from the TSI nanoscan and TSI Condensation Particle Counter measured in the veterinarian's breathing zone.

Control		Procedure	N	Q1, 25th percentile	Mean	Median	Q3, 75th percentile	Maximum	Standard deviation	Collection efficiency, %
	Nanoscan	Background	5	2,166	2,360	2,489	2,652	5,050	848	
None		Surgery	5	1,671	25,865	2,670	4,966	3,430,075	186,020	
	CPC	Background	5	1,337	1,503	1,619	1,752	2,322	367	
		Surgery	5	1,221	6,330	1,911	3,202	443,528	24,796	
	Nanoscan	Background	6	1,180	1,879	1,932	2,522	3,421	749	
SES		Surgery	6	1,395	7,800	2,332	3,984	2,231,230	66,121	70
	CPC	Background	5	1,001	1,542	1,404	1,744	3,117	636	
		Surgery	5	1,101	4,054	1,838	2,922	322,729	10,353	36

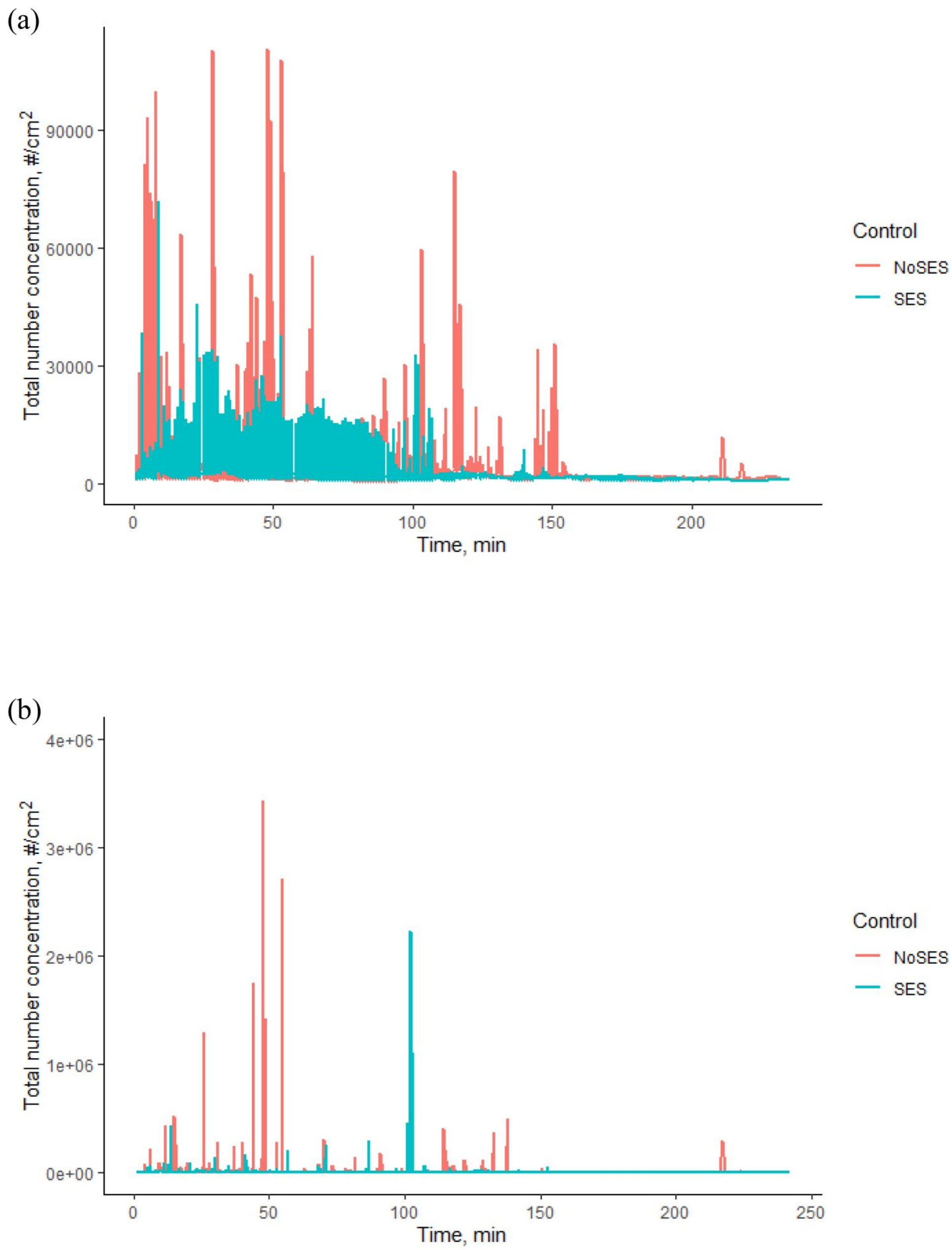

Figure 2. Time series of average particle number concentration from the (a) CPC with and without SES and the (b) TSI nanoscan with SES ($n = 6$) and without SES ($n = 5$). The nanoscan failed for one trial without the SES. Due to COVID-19 we were unable to collect additional data.

SMPS by a ratio of 1.33. The authors posited that the agglomerate structure of the particles resulted in mischarging and particle overcharge, causing an overestimation of the total particle concentration. Similarly, Jørgensen (2019) compared the performance of a Scanning Mobility Particle Sizer (model 3938 L76, TSI Incorporated, Shoreview, USA), Fast Mobility Particle Sizer (FMPS, model 3091, TSI, Shoreview, MN, USA), handheld condensation particle counter (CPC, model 3007, TSI, Shoreview, MN, USA), and a NanoScan SMPS (model 3910, TSI, Shoreview, MN, USA) under four different exposure scenarios (MIC welding fume, PVC welding, cooking fume, and candle burning). Concentrations measured varied widely based on the exposure scenario and instrument. They also found that the Nanoscan reported a higher total number concentration during the cooking scenario compared to the CPC (ratio of 2.8). Buonanno et al. (2009) showed that particles generated from cooking and burning incense tend to be agglomerated particles. Particle morphology was not assessed in this study; however, it is anticipated that the morphology was similar to particles generated from cooking meat and that the aggregated particle structure may have resulted in overestimation of the total particle concentration from the Nanoscan, similar to Stabile et al. (2014) and Jørgensen (2019)'s hypotheses. Similar to previous exposure assessments in human surgeries, this study found high peak particle number concentrations during canine limb amputation surgery (Buonanno et al. 2019; Carr et al. 2020; Lee et al. 2018; O'Brien et al. 2020). Figure 2 shows the time-series number concentrations with and without SES from the Nanoscan. Over half of the total number concentration occurred within the first half of the surgery (Figure 3), which corresponded to when the greatest number of peak concentrations from electrocautery use occurred. Instantaneous peak number concentrations ranged from 4.3×10^5 to 3.4×10^6 #/cm^3 without the SES and from 5.3×10^4 to 4.2×10^5 #/cm^3 with the SES present, highlighting the effectiveness of SES in reducing the peak concentrations that occurred during electrocautery use.

Size-distribution

Like studies conducted in human surgeries, particle sizes generated during surgery were predominantly small, with particle sizes ranging from 100 to 400 nm. Figure 4 displays the size distributions averaged across trials measured during surgeries with and without SES. The average count median diameter (CMD) decreased slightly from 70 nm without SES to 51 nm when SES was used; particle sizes of concern because it is within the size range where peak penetration

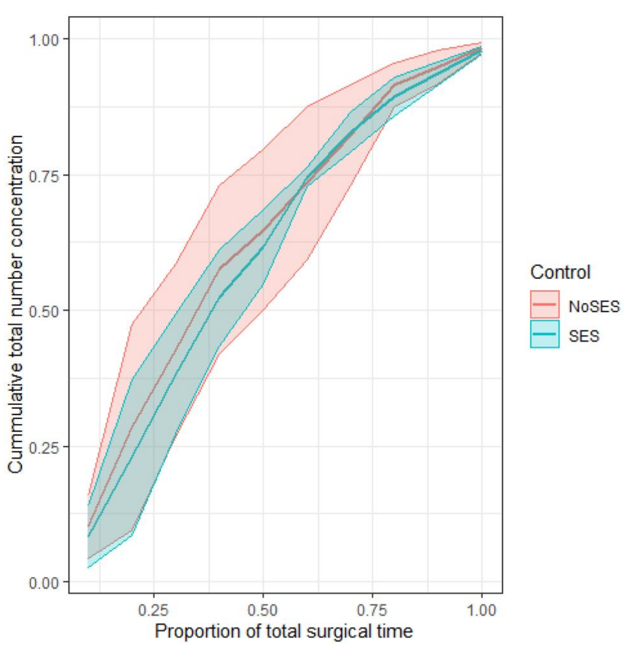

Figure 3. Cumulative total number concentration *vs.* proportion of total surgical time.

through filtration media for some models of surgical masks occur (Rengasamy et al. 2009). While the CMD was slightly lower for surgeries with SES present, the shift in the CMD was not significant (p-value = 0.18, Kruskal-Wallis Rank Sum test). The largest reductions in particle number concentrations when employing the SES occurred between particle sizes 86.6 and 154 nm, with about a 76% reduction in particle concentrations.

Discussion

This study offers important insights into the particle concentrations measured in a veterinary hospital. Average particle number concentrations without SES present measured in this study ranged from 2,700 to 1.1×10^4 #/cm^3 with the CPC, and from 1.2×10^4 to 5.8×10^4 #/cm^3 for the Nanoscan. Ragde et al. reported concentrations ranging from 400 to 3,900 #/cm^3 (Ragde et al. 2016) when sampling for the entire surgery duration using a TSI 3091 FMPS with the conductive sampling tube located on the participant's left shoulder. Liu et al. reported an average particle concentration of 1,600 #/cm^3 (Liu et al. 2020) measured during spinal surgeries using a CPC (TSI, P-Trak, model 8525, TSI Inc., Shoreview, MN). Carr et al., however, reported particle concentrations ranging from 8,200 to 7.8×10^4, and noted that concentrations were dependent on the power level of the cautery tool and type of surgery performed (Carr et al. 2020). Carr et al. (2020) used a Diffusion Size Classifier miniature (DiSCmini v1.0; Matter Aerosol AG, Wohlen, Switzerland), which uses diffusion charging to separate and measure particles from 20 to 300 nm to measure exposures for the duration of a pediatric tonsillectomy. Buonanno et al. (2019) reported concentrations ranging from 7,000 to 1.0×10^4 #/cm^3 (Buonanno et al. 2019). Buonanno et al. (2019) used a Nanotracer which uses diffusion charging to separate and measure particles from 10 to 300 nm calibrated against a CPC and SMPS (TSI Model 3936). Different instruments have varying abilities to detect particles of different sizes, thus, some differences in reported total particle concentrations may be due to the use of different sampling methods/instrumentation. The TSI P-TRAK measures a wider size range (20 to 1,000 nm) compared to the FMPS, Nanotracer, and Nanoscan (5.6 to 560 nm, 10–300, 10–420 nm, respectively). However, several studies have hypothesized that the Nanoscan overestimates particle concentration when particles are agglomerated (Buonanno et al. 2009; Stabile et al. 2014). This

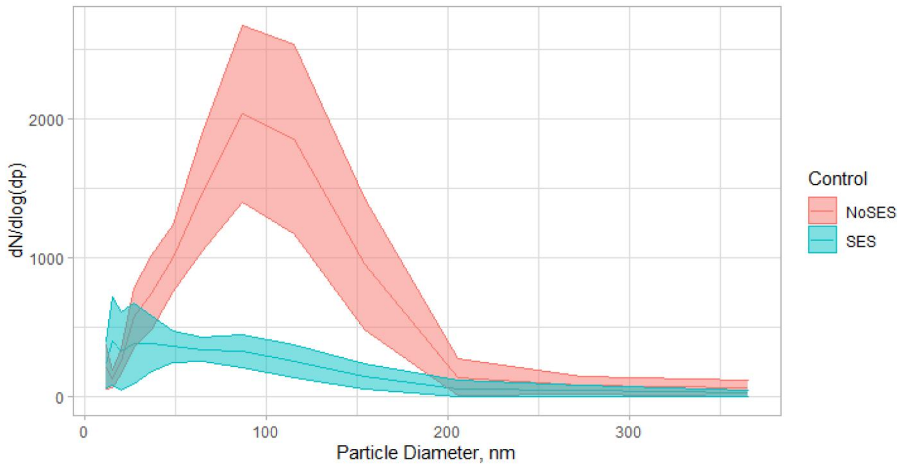

Figure 4. Normalized size-distribution of particles measured during canine amputations with SES ($n=6$) and without SES ($n=5$). The Nanoscan failed for one trial without the SES. Due to COVID-19 we were unable to collect additional data. The centerline represents the average across all six trials, the shaded region represents the 95th percentile. dN/dlog(dp) represents number concentration of particles as a function of their size.

highlights the need for standardized methods for measuring surgical smoke to better understand factors impacting exposure levels and health outcomes.

Similar to surgeries on human patients, this study found high particle concentrations that were predominantly driven by short-term peak exposures. Maximum particle number concentrations for trials without SES ranged from 3.8×10^5 to 4.4×10^5 #/cm^3 for the CPC and 4.3×10^5 to 3.4×10^6 #/cm^3 for the Nanoscan, similar to peak concentrations reported in other studies (Buonanno et al. 2019; Carr et al. 2020; Lee et al. 2018; O'Brien et al. 2020; Seipp et al. 2018).

Depending on the instrument used, this study measured a 36–70% reduction in total particle number exposure when using a smoke evacuation pen, which is comparable to capture efficiencies reported by other studies evaluating surgical smoke reduction using smoke evacuation pens in human surgeries. Laboratory studies evaluating SES in ideal conditions report high capture efficiencies ranging from 95 to >99% efficiency, but noted these high capture efficiencies were dependent on cutting angle and high suction flow rates (Seipp et al. 2018). Capture efficiencies for SES in field investigations vary widely, ranging from 44% to ~94%. Geier et al. (2022) evaluated the efficiency of a smoke evacuation electrocautery pencil during canine surgery and reported a capture efficiency of 56% and statistically significant reductions in average particle concentrations (Geier et al. 2022). Similarly, Liu et al. reported a 44 and 60% reduction in mean particle number concentration during the first stage of spinal surgery when using smoke evacuation pencils and a para-incisional evacuator, respectively (Liu et al. 2020). However, Carr et al. and O'Brien et al. reported higher capture efficiencies ranging from 80 to 94% for smoke evacuation cautery pencils during pediatric tonsillectomy and adenoidectomy surgeries which makes sense given the smaller volume in the mouth and nasal cavity that would have resulted in increased air changes from the SES near the tip of the instrument (Carr et al. 2020; O'Brien et al. 2020). Capture efficiency of SESs is dependent on many factors, including the flow rate for the exhaust of extraction of the SES, and the angle and distance of the SES relative to the electrocautery tip. The impact of these factors on particle and gaseous surgical smoke contaminants needs to be better characterized and understood to develop effective exposure mitigation strategies.

Particle exposures measured in human surgical suites have been reported to be significantly higher than background levels, indicating these exposures may be poorly controlled. Surgical smoke exposure is an emerging concern in operating rooms, and several states have passed or are considering bills requiring smoke evacuation systems in human operating rooms. While epidemiological studies on health outcomes associated with surgical smoke exposure among human surgeons or veterinarians are limited, animal models have shown that exposure to surgical smoke causes acute and chronic inflammatory changes in the respiratory tract. One study reported histopathological changes in the nasal mucosa in 70% of medical residents after 4 years of exposure to SS during surgical rotations (Navarro et al. 2016), while another study reported changes in the blood count of neutrophils and lymphocytes (Lopez et al. 2016). While few studies have evaluated the long-term effects of chronic exposure, several chemicals measured in surgical smoke are carcinogenic or suspected to be carcinogenic, warranting further investigation.

Furthermore, veterinary surgical suites differ from human surgical suites in several ways that could contribute to higher particle exposure levels in veterinary settings. Recommended ventilation rates from the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) differ between veterinary clinics and human surgical suites. For human surgical suites, ASHRAE Standard 170 Ventilation of Healthcare Facilities recommends a minimum of 20 air changes per hour (ACH) with at least four of those being outdoor air, to maintain positive pressure in the surgical suite to prevent infiltration of unwanted air and to provide a sterile environment and prevent infections. Conversely, ASHRAE 170 recommends a lower minimum ACH requirement for veterinary surgical suites, often around 15, reflecting the different infection control needs and the diverse types of procedures performed. Both settings emphasize maintaining positive pressure to prevent the ingress of contaminants, but the specific rates and additional measures, such as humidity control and temperature regulation, may vary, tailored to the unique demands of human *vs.* animal healthcare environments. The lower recommended ventilation rates for veterinary clinics may contribute to higher potential exposures to surgical smoke.

Moreover, veterinary surgical suites can vary widely in size and layout depending on the type of practice and procedures performed. Veterinary surgical suites may often be smaller and may have limited space compared to human surgical suites. This compact environment can lead to higher concentrations of surgical smoke, especially if adequate ventilation systems are not in place. In larger animal hospitals, there may be multiple surgical beds in a single room. The anatomy and physiology of animals differ from humans, and this can impact the composition and quantity of surgical smoke generated during procedures. Personal protective equipment use in veterinary clinics may be less standardized or enforced compared to human surgical settings. This may result in inadequate protection against surgical smoke for veterinary staff, increasing their risk of exposure to hazardous airborne particles. Awareness of the health hazards associated with surgical smoke exposure may be lower in veterinary clinics compared to human hospitals. Lack of comprehensive training on smoke evacuation techniques and safety protocols can contribute to higher exposures among veterinary personnel. While smoke evacuation devices exist for veterinary use, their adoption and utilization rates may be lower due to cost constraints, lack of awareness, or perceived inconvenience. Several factors contribute to a surgeon's willingness to adopt smoke evacuation systems in the operating room, including concerns about noise, comfort, visibility, and cost that need to be accounted for. This can result in inadequate removal of surgical smoke during procedures.

Limitations

Although this is the first study to evaluate surgical smoke particles during canine limb amputation in animal hospitals, it should be noted that this study was a small pilot study ($n = 6$ dogs) and evaluated one veterinary surgical procedure. Given the large variability seen in human surgeries, additional surgical procedures, animals, and surgical bay set-ups should be investigated.

It is important to note, this pilot study was conducted in a one-bed surgical suite, separated from the rest of the veterinary clinic. Thus, the layout was similar to human surgical suites, which may be why there appears to be agreement in particle concentrations measured in this study compared to human surgeries.

Other factors that could impact particle exposures in surgical smoke include the duration and frequency of electrocautery use during surgery, the power setting and waveform on the electrocautery unit, angle of the electrocautery pen, and distance of the electrocautery pen to the smoke evacuation system. This study evaluated the use of electrosurgery and smoke evacuation systems in a field investigation, thus, factors beyond the use (or not) of the SES were not controlled. Controlled laboratory studies evaluating the impact of these factors are needed to develop exposure models and better understand their impact on SES effectiveness. Future work should focus on characterizing these factors and understanding their impact on particle exposures in veterinary clinics.

Furthermore, surgical smoke produced when cutting and cauterizing tissues and blood vessels generates particles and hazardous compounds that vary in concentration and composition depending on the procedure. Although this pilot study only evaluated particle exposures during canine amputation, future exposure assessments should also characterize the vapors and gaseous components in surgical smoke and evaluate the correlation between particle emissions and other contaminants.

Only one SES was evaluated. However, multiple SESs are commercially available, and designs range from those with the SES incorporated in the electrosurgery pen to wall units that are positioned near the surgical site. A more comprehensive evaluation of SES units should be conducted for exposure reduction efficacy, noise, visibility of the surgical field, comfort, and ease of use. Moreover, future work should focus on evaluating the barriers and aids to adopting SES to better design intervention studies with a high likelihood of adoption.

Conclusions

Overall, reductions in particle exposures can be achieved with the use of SES. However, factors impacting SES capture efficiency of particle and gaseous surgical smoke contaminants need to be better characterized and understood to develop effective exposure mitigation strategies. Given the high variability in concentration and size distribution between surgery types in humans, further evaluation of the potential occupational exposures among veterinary personnel is warranted. More research is needed to encompass a wider range of surgery types, electrosurgery types, and animals to confirm these findings and to determine if a layered mitigation approach is necessary for protecting worker health. Furthermore, additional research is necessary to characterize gaseous components present in surgical smoke generated from veterinary surgical procedures, as well as epidemiological studies to elucidate the long-term health effects from chronic exposure to surgical smoke. This study highlights the need for standardized methods for measuring surgical smoke to better understand factors impacting exposure levels and health outcomes and allow for comparisons between studies.

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Disclaimer

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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