



Effects of operating room ventilation on particle exposure and removal during general endotracheal anesthesia

Muchuan Niu^a, Haoxuan Chen^a, Jonathan Liu^a, Chi-hong Tseng^b, John Shin^c, Nir Hoftman^c, Yifang Zhu^{a,*}

^a Department of Environmental Health Sciences, Fielding School of Public Health, University of California Los Angeles (UCLA), Los Angeles, CA, 90095, USA

^b Department of Medicine, David Geffen School of Medicine, University of California Los Angeles (UCLA), Los Angeles, CA, 90095, USA

^c Department of Anesthesiology, David Geffen School of Medicine, University of California Los Angeles (UCLA), Los Angeles, CA, 90095, USA

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ABSTRACT

The operating room (OR) ventilation system is a primary method for reducing particle exposure in the OR. However, most ventilation studies in operating rooms were conducted using computational fluid dynamics (CFD) models, which may not be able to predict the complexity of real operating conditions. In this study, we recruited 40 patients undergoing general endotracheal anesthesia in a total of 13 operating rooms. We tested the effectiveness of OR ventilation on mitigating patient and nebulizer-generated particles during the preoxygenation, induction, and intubation phases of care. Sampling locations were selected close to the patient's face (reference), physician's head area, and medical assistant's standing location. A total of six sampling sessions characterizing patient and healthcare worker activities were included. We observed a significantly higher number of particles during endotracheal intubation compared to preoxygenation with deep breathing and coughing, suggesting potential disruptive effect of surgical activities (i. e., intubation) on airflow, which affected particle concentration. Particle decay rates measured at all three locations (reference $50 \pm 20 \text{ h}^{-1}$; physician $46 \pm 22 \text{ h}^{-1}$; medical assistant $33 \pm 21 \text{ h}^{-1}$) were considerably higher than the regulated operating room air exchange rate of 20 h^{-1} , indicating highly effective overall ventilation function. Nevertheless, healthcare workers should still be cautious about particle exposure risks in operations that generate large number of particles. Results from this study reflect the effectiveness of OR ventilation on particle mitigation in real-world scenario and may facilitate the validation of future CFD studies as well as the establishment of effective OR regulation guidelines to protect healthcare workers from particle exposures.

1. Introduction

Health care workers (HCWs) play a critical role in ensuring public safety and wellbeing [1,2]. However, HCWs are at higher risks of infections during public health crises such as Coronavirus Disease 2019 (COVID-19) as they work in close proximity to infected patients while performing surgical procedures and thus may inhale virus-laden particles emitted by the patients in indoor settings [3–6].

Abbreviations: AER, Air exchange rate; HCW, Health care workers; HEPA, High-Efficiency Particulate Air; LAF, Laminar airflow; OR, Operating room; PNC, Particle number concentration; TMA, Turbulent mixing airflow; UFP, Ultrafine particle.

* Corresponding author. UCLA Fielding School of Public Health, 650 Charles E. Young Drive South, 51-295B CHS, Los Angeles, CA, 90095, USA.

E-mail address: yifang@ucla.edu (Y. Zhu).

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Statistics from early in the COVID-19 pandemic have shown high infection rate and hospitalization rate for HCWs worldwide [7,8]. The World Health Organization estimated a median scenario of 115,000 deaths globally for HCWs during the first year of the COVID-19 pandemic [9].

The operating room (OR) is considered a high risk environment for HCWs in a hospital as they could be exposed to pathogens containing aerosol particles in the sizes of fine ($PM_{2.5}$, particles $<2.5\ \mu\text{m}$ in diameter) and ultrafine particles (UFPs, particles $<0.1\ \mu\text{m}$ in diameter) during surgical procedures and patient respiratory activities [10–12]. PM exposures have been generally associated with various adverse health effects including cardiovascular diseases, respiratory malfunctioning, and inflammatory illness [13–15]. The exposure risks for HCWs become further elevated during aerosol generating medical procedures including endotracheal intubation during general anesthesia [16] when HCWs are directly challenged by respiratory particles emitted from the patient's throat [17]. The aerosol plume resulted from patients' coughing and sneezing contains respiratory particles that may infect HCWs around the surgical table through surface contact or airborne transmission within a close proximity of 2 m [4,18]. Evidence has suggested that respiratory particles may be carried to a longer distance of 7 to 8 m due to turbulent respiratory event (i.e., coughing and sneezing) and affecting susceptible individuals at further distances [19]. The viable viral contents within respiratory particles can live up to 72 h and transmit infection through deposition onto respiratory epithelium [20]. A recent research has measured aerosol particles generated from volitional coughs initiated by the patients during endotracheal intubation and found that the mean particle number concentration (PNC) of volitional coughs was 35-fold higher than the PNC measured during intubation when patients were put into asleep [21], suggesting high exposure risks during respiratory events.

Surgeries that generate surgical smoke are also considered high risks as previous studies have demonstrated the presence of multiple viruses transmission through surgical smoke including human immunodeficiency virus, hepatitis B virus, and human papillomavirus [22]. Surgical smoke particles often lie within the range of $<0.1\ \mu\text{m}$ – $5\ \mu\text{m}$ depending on the operating methods used and contain viable or non-viable viral contents which subsequently poses risks of infections [23]. It is estimated that over 500,000 HCWs are exposed to surgical smoke [24] and various adverse health effects have been documented including eye, nose, and lung irritation, asthma symptoms, and chronic inflammation [23,25,26]. A few studies quantifying particles generated from surgical smoke have reported high PNC levels in the OR [27]. Li et al. [28] characterized particles created during otorhinolaryngology and found peak PNC levels of greater than 10^6 particles/ cm^3 . Other studies investigating abdominoplasty, nephrectomy, and otologic drilling have reported peak PNCs exceeding 10^5 particles/ cm^3 [29,30]. These findings indicated the likelihood of extremely high particle exposures during surgical operations, which highlights the needs for mitigating and eliminating aerosol particles to protect HCWs from exposure risks in the OR [31,32].

The ventilation system installed in the OR is the primary method of removing contaminated aerosol particles [33]. Two major ventilation systems are widely adopted in ORs: turbulent mixing airflow (TMA) system [34] and laminar airflow (LAF) system [35,36]. The TMA system dilutes aerosol contamination to a lower level through turbulent mixing between sterilized air supply and the room air; while the LAF system directs unidirectional air from the central ceiling down towards surgical table to create an ultra-clean zone and wash away the contaminants from the operating area [37]. Studies on the effectiveness of OR ventilation system generally applied computational fluid dynamics (CFD) models. A CFD modelling study investigating air exhaust configurations suggested a 64 % reduction in total number of deposited particles at the size of $5\ \mu\text{m}$ under LAF systems [6]. Another study using CFD model simulated the dispersion of particles at the sizes of $5\ \mu\text{m}$, $20\ \mu\text{m}$, and $100\ \mu\text{m}$ in an intensive care unit and found lower particle suspension rates for LAF systems compared to TMA systems [38]. Other published CFD modelling studies assessed the effects of OR ventilation in preventing surgical site infections by reducing microbiological particles in the size range of 0.5 to $20\ \mu\text{m}$ [39–41]. Nevertheless, CFD models have practical limitations as the modelling processes are dependent on the selection of environment and building parameters and often lack sufficient measurements to accommodate variations in real OR settings. Thus, CFD models cannot emulate the complexity of the OR environment seen in real-world scenarios [34]. In addition, these OR ventilation studies have neglected the quantification of UFPs in most cases and the analyses only considered particles larger than $0.5\ \mu\text{m}$ [21,42]. A lack of regulatory guidelines likely contribute to the limited research on UFP mitigations in the OR [31]. The current International Organization for Standardization (ISO) cleanroom classification [43] and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 170 Standard [44] applied in ORs have only specified concentration limits for particles larger than $0.1\ \mu\text{m}$, thus creating a normative gap on UFP regulation in the OR cleanroom environment [32].

In this study, the effectiveness of ventilation system in the ORs of a major hospital was evaluated under real-world operating condition during general endotracheal anesthesia. Particles generated from patient's respiration and a saline nebulizer were sampled and compared at three locations where HCWs perform operating procedures. A total of six test sessions representing patient and HCW activities was incorporated during the test. Particle decay rate was determined and generalized to other particle generating procedures to inform potential particle exposure levels. Results from this study reflect the effectiveness of OR ventilation on particle mitigation in real-world scenarios and may facilitate the validation of future CFD studies as well as the establishment of effective OR regulation guidelines to protect HCWs from particle exposures.

2. Methods

The study took place in the ORs of a major hospital from July to September 2021. All patients recruited in this study were interviewed and signed a written informed consent prior to participation. The study was approved from the Medical Institution Review Board (IRB) at UCLA (21–000022). No patient data were retained for the purpose of analysis in this study.

2.1. OR specification and ventilation installation

A total of 13 ORs installed with TMA system were included in this study. Ventilation inlets for all ORs were located on the central ceiling directly above the surgical table [45]. Exhaust evacuation outlets were located close to the floor level on the surrounding walls. The schematic diagram of the OR ventilation is shown in Fig. 1A.

Air flows into the OR through the air inlets via central ceiling ventilation which is filtered by pre-installed High-Efficiency Particulate Air (HEPA) filters [46]. Air injected to the OR from the ceiling is evacuated through floor level exhaust outlets, a process which facilitates active indoor air mixing. The overall air exchange rate (AER) for all ORs satisfies the ASHRAE 170 Standard at 20 times per hour (h^{-1}) [44]. For the 13 ORs involved in this study, the mean room volume was $155 \pm 20 \text{ m}^3$. The ratios between the sizes of air inlets and exhausts outlets were comparable across all ORs, suggesting small variations in the overall air mixing and removal capacity in different ORs (Table S1). The OR volume and ventilation grill sizes are comparable to published studies focusing on OR ventilation and particle measurements (Table S2) [31,47–49].

2.2. Aerosol sampling

2.2.1. Aerosol generation

Aerosol particles were generated using a small volume nebulizer (model: AirLife Misty Fast, Vyaire Medical Inc., IL, USA) containing 5 mL of normal saline solution (NaCl). We first tested the particle generation of the nebulizer in a chamber of dimensions $0.45 \text{ m} \times 0.45 \text{ m} \times 0.5 \text{ m}$ for 1 min. At the flow rate of 2.0 L/min, the mean PNC level was at $10^5 \text{ particles/cm}^3$ (Fig. S1), which is at the peak

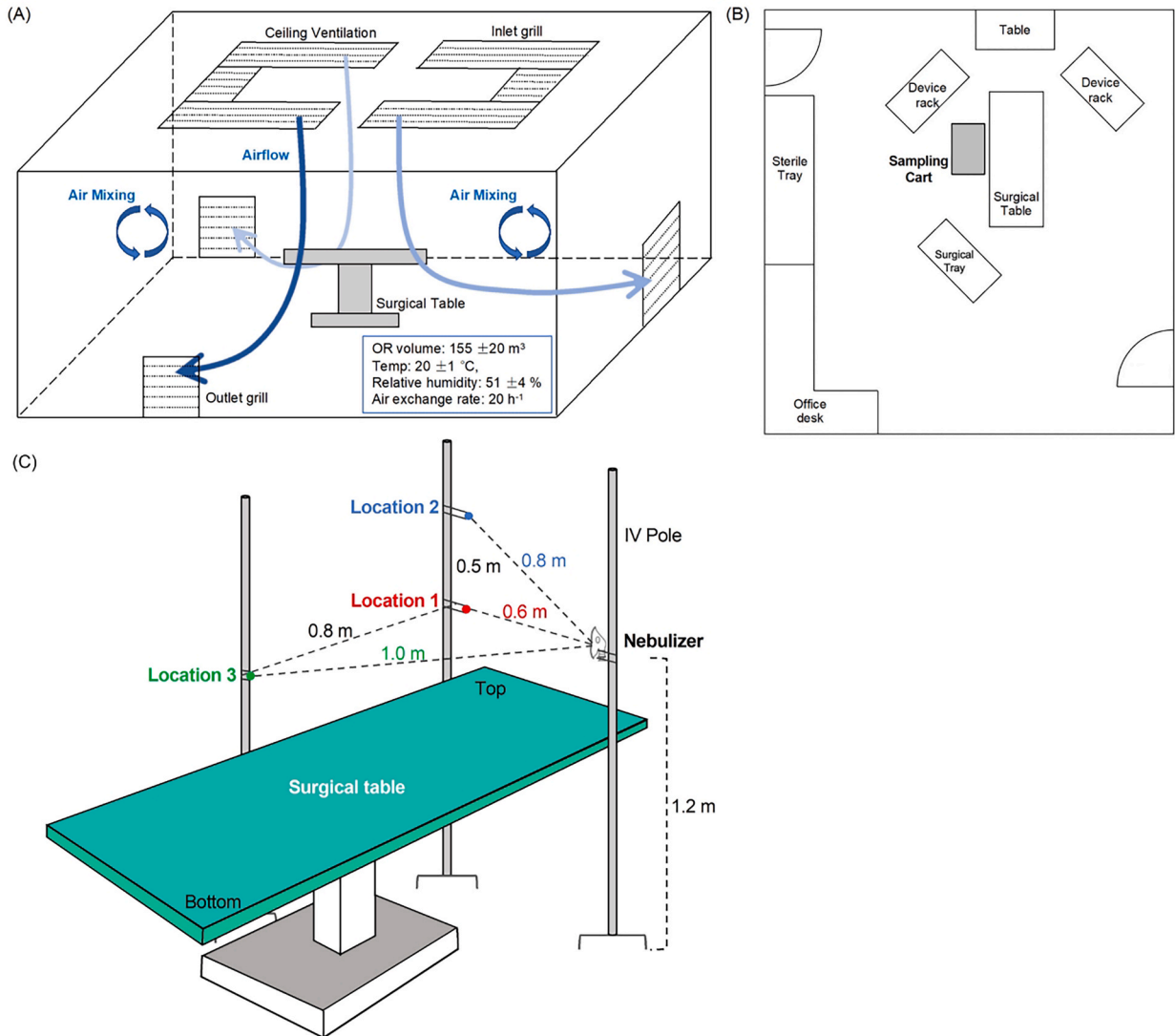


Fig. 1. (A) Schematics of TMA ventilation installation in the tested ORs. (B) Floor plan of the tested ORs including the placement of the sampling cart. (C) Setup of the saline nebulizer and three particle sampling locations: Location 1 (reference), Location 2 (physician), and Location 3 (medical assistant).

PNC levels detected from various reviewed surgeries [28,30] (Table 1). In the OR, the nebulizer was connected to a wall-source oxygen supply and functioned at a constant flow rate of 2.8 L/min. The nebulizer was mounted on an intravenous (IV) pole on one side of the surgical table toward the head area, which was in close proximity to the patient's face (Fig. 1C). The nebulizer was used to constantly generate particles to facilitate continuous sampling.

2.2.2. Sampling locations

A total of three sampling locations were selected as shown in Fig. 1C. The first sampling location (Location 1) was at the side of the surgical table, 0.6 m lateral to the nebulizer. The sampling inlet was mounted on an IV pole at the same height as the nebulizer, 1.2 m above the floor. This location was the closest to patient's face and is treated as the reference for analysis. The second sampling location (Location 2) was placed 0.5 m above Location 1 on the same IV pole ($0.5 + 1.2 = 1.7$ m), 0.8 m from the nebulizer. Location 2 captured the particle levels at the physician's head area. The third sampling location (Location 3) was at the waist side of the surgical table, 1.2 m above the floor and 1.0 m away from the nebulizer. Particles detected at this location captured the exposure for nurses and medical assistants. These locations were selected as they represented typical working locations for HCWs under real operating conditions in the OR [50].

2.2.3. Instrumentation

Real-time PNC was measured at all three sampling locations simultaneously using Condensation Particle Counter (CPC 3007, TSI Inc., MN, USA), with a sampling size range of 10 nm to $> 1 \mu\text{m}$. All CPCs were placed on a medical supply cart right next to the surgical table (Fig. 1B). The data logging interval for all three CPCs were set to 1 s. An indoor air quality monitor (Q-Trak 7575, TSI Inc., MN, USA) was used to measure OR temperature and relative humidity (RH), which was placed by the sidewall of the OR. The data logging interval for the Q-Trak was set to 1 min. We monitored the oxygen flow rate going through the saline nebulizer using a Mass Flow Meter (4100 series, TSI Inc., MN, USA), which provided instantaneous flow rate readings.

All other surgical instruments including sterile trays, scalpels, forceps, and equipment for intubation such as video laryngoscope (Glidescope, Verathon Inc, WA, USA) were remained in their designated operating locations [51].

2.3. Study design

Particle sampling was conducted during general endotracheal anesthesia prior to patients' undergoing elective surgeries. A total of six 1-min sampling sessions were incorporated (S1-S6) representing patient respiratory activities and surgical operations:

Table 1
PNC generated from selected surgeries and expected PNC after short period of time.

Study	Sampling instrument	Surgical procedure	Total cases reported	Sampling location	Peak exposure (PNC, cm ⁻³)	Expected PNC (cm ⁻³)	
						After 1 min	After 10 min
Ragde et al., 2016 [30]	TSI3091 FMPS (5.6-560 nm)	Abdominoplasty Nephrectomy	3	Physician	148,000	6400	4
			3	Physician	741,200	322,000	180
			3	Medical assistant	114,000	65,600	460
		Breast reduction	3	Physician	123,000	53,400	30
			3	Medical assistant	272,000	157,000	1100
		Hip replacement	7	Physician	123,000	53,400	30
			4	Medical assistant	123,000	70,800	500
Li et al., 2022 [28]	HAL-HPC300 (0.3-10 μm)	Otorhinolaryngology	30	On surgical table ^d	>1,000,000	>434,000	>240
				Medical assistant	>100,000	>57,600	>400
Lahelma et al., 2022 [29]	TSI3330 OPS (0.3-10 μm)	Otologic drilling	13	Outside surgical table ^e	1353	780	5
Murr et al., 2021 [71]	VPC300 (0.3-10 μm)	Endoscopic Sinonasal drilling	5	Physician	10,000	4300	2
Buonanno et al., 2019 [47]	NanoTracer (10–300 nm)	General surgery ^a	12	On surgical table	70,000	40,300	280
		Orthopedic surgery ^b	14	On surgical table	52,000	29,900	210
		Caesarian section	5	On surgical table	58,000	33,400	230
		Major surgery ^c	6	On surgical table	24,000	4000	30

^a General surgery includes hernia repair, cyst removal, circumcision, phlebotomy, and appendicitis.

^b Orthopedic surgery includes prosthesis/endoprosthesis implantations and fracture reduction.

^c Major Surgery includes laparoscopic hysterectomy, myomectomy, hemicolectomy, bowel obstruction removal, and etc.

^d At this location, the decay rate at Location 1 (reference) was applied for calculation.

^e At this location, the decay rate at Location 3 (medical assistant) was applied for calculation. Peak exposures were identified for each surgery at different locations around the surgical table. Expected PNCs after 1-min and 10-min decay were calculated using the decay rate obtained from this study.

S1: OR baseline, patient quiet breathing; S2: Nebulizer baseline, nebulizer activated, patients remain quiet breathing; S3: Deep breathing & coughing, patient deep breathing (30 s) and coughing (30 s) alternating; S4: Induction of anesthesia, HCWs prepare for anesthesia, patients induced to anesthesia (if longer than 1 min, the first minute of the session was selected for analysis); S5: Intubation, endotracheal airway management (if longer than 1 min, the first minute of the session was selected for analysis); S6: Recovery, nebulizer deactivated, particle decay was measured.

All experimental parameters including sampling session descriptions are summarized in Table S3.

2.4. Quality control and quality assurance

All CPCs were calibrated, cross-located, and aligned in time before each test. CPCs were warmed up for more than 5 min before each test to ensure stable device functioning and accurate sampling. All devices were carefully monitored by onsite researchers throughout the test to avoid battery shortage and connection errors. Activities that might affect data collection, such as patient talking and blocking of sampling inlets by HCWs were recorded by onsite researchers. Adjustments on the oxygen flow rate were made in situations when the wall-source oxygen output deviated from 2.8 L/min.

2.5. Statistical Analysis

Summary statistics on OR ventilation specifications and indoor environment parameters (temperature, RH) were compiled using means and standard deviations. *Shapiro-wilk test* for normality was applied to the 1-s real-time PNC data collected at three sampling locations during each session. Data collected were analyzed using *geometric means* to accommodate skewed PNC data. Non-parametric *paired Wilcoxon signed-rank test* was used to compare the geometric mean PNCs between any two locations and sessions. *Kruskal-Wallis one-way ANOVA (analysis of variance)* was conducted to compare the geometric mean PNCs within three sampling locations for each sampling session.

Particle decay rate was calculated for the decay session (S6) based on the following equation [52]:

$$-\ln(C_t / C_0) = k \times t \quad (1)$$

where C_t is the measured PNC (particles/cm³) at time t . C_0 is the initial PNC at the start of the decay session (S6), presumably the highest PNC of the decay period. Particle decay rate is expressed by k (h⁻¹), which is the coefficient of the best fitted decay curve in S6. All decay sessions of the 40 patients were screened individually to exclude sessions with flat or no decay based on each PNC time series curve. Based on this observation, we identified eligible decay sessions with a cutoff PNC of 500 particles/cm³ initially at three sampling locations. A total of 23, 24 and 9 decay sessions were selected for analysis at Location 1, 2, and 3, respectively. *Student t-test* was used to compare the mean decay rate between locations.

Statistical significance was set at a two-sided alpha level of 0.05 ($p < 0.05$). Data analyses were conducted using statistical software R Studio, version 1.2.5019 [53].

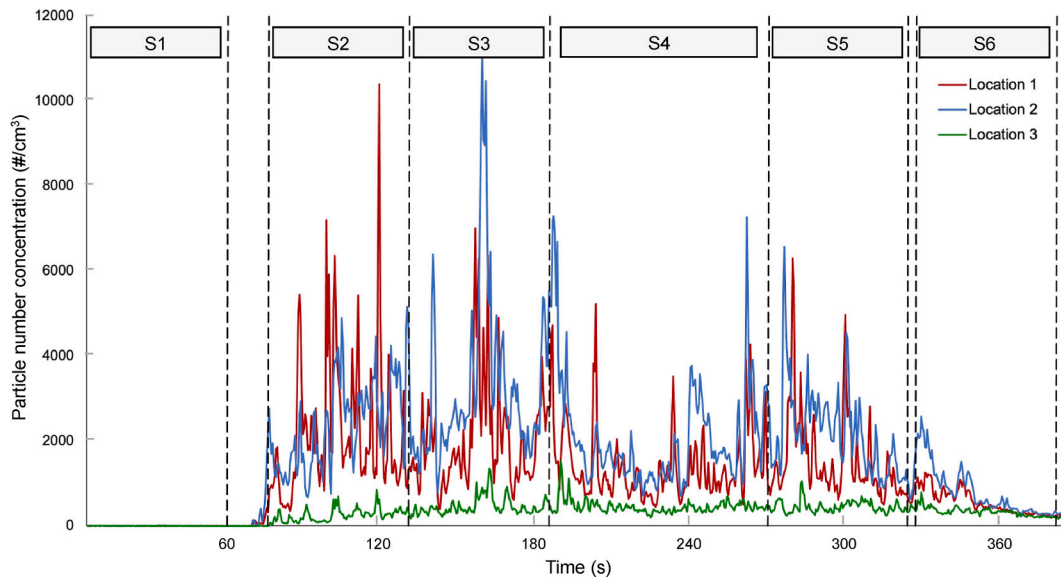


Fig. 2. PNC time series at three sampling locations for a typical patient. Location 1 was the reference location close to the patient's face and nebulizer source. Location 2 was at the physician's head area. Location 3 was at the waist of the surgical table representing the location for medical assistants. Red, blue, and green lines represent Locations 1, 2, and 3, respectively. Sessions 1 to 6 (S1 to S6) are framed in dashed vertical lines. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3. RESULTS and DISCUSSION

3.1. PNC time series at three sampling locations

Fig. 2 illustrates the PNC time series for a typical patient at Locations 1, 2, and 3. Activation of the nebulizer after the baseline session (S1) resulted in elevated PNCs in S2, S3, S4, and S5, at Location 1 (reference) and Location 2 (physician's head area), respectively. The PNC spikes observed at Location 1 and Location 2 during S2, S3, S4, and S5 were well correlated, suggesting synchronized increases in particle levels at these two locations. The PNC level at Location 3 was lower compared to those at Locations 1 and 2 and showed only minor spikes throughout the test. S6 presented particle decay at all three sampling locations when the nebulizer was deactivated.

3.2. PNC comparisons between test sessions and locations

Fig. 3 illustrates the geometric mean PNCs for all 40 patients. When the nebulizer was activated in S2, the geometric mean PNCs in the following sessions increased dramatically and remained at higher levels compared to the baseline (S1).

Using paired Wilcoxon signed-rank test, we compared the PNCs at S5 (intubation) with S2, S3, and S4, respectively. Significantly higher PNCs were detected between S5 and S2 (nebulizer baseline) at Locations 1, 2, and 3; between S5 and S3 (patient deep breathing and coughing) at Location 3; and between S5 and S4 (induction of anesthesia) at Location 2. As the generation of particles was constant, the increase in PNC observed in S5 might be attributable to the disruptive effect of surgical procedures associated with endotracheal intubation, which disturbed airflow and altered particle concentrations [54]. Standard intubation procedures typically involve preoxygenation, induction, mask ventilation, mechanical ventilation, and tracheal intubation [42,51], which require the anesthetist to approach the patient's head and actively move his/her upper body and arms. These procedural activities potentially affected the airflow distribution and blocked particle transport passage, which compromised the effectiveness of ventilation and contributed to higher particle exposures [55]. Future research could investigate the particle concentrations during surgeries that involve different operating procedures at various locations around the surgical table to analyze localized disruptive effects.

Further, we noted a progressive increase in both the mean and median PNCs at all three sampling locations, starting from S2 to S5 until the nebulizer was deactivated in S6 (Fig. 3). We postulate that the higher PNCs observed in the latter part of the test could be attributable to the gradual accumulation of aerosol particles due to obstacles such as surgical appliances and medical personnel (i.e., HCWs). Previous CFD study had identified significantly lower airflow velocity around a surgical lamp than that of the surrounding OR environment, which was associated with the formation of an air recirculating zone and the accumulation of aerosol particles [56]. In addition, medical personnel in the OR have been shown to affect ventilation efficiency as long as they are in the middle of the exhaust air evacuation trajectory in both CFD modeling and controlled laboratory settings [39,55,57]. As there were about 10 HCWs around the surgical table during surgery in this study, the potential effect of obstacles could be substantial. In addition to the surgical table area and its direct surroundings, published CFD studies also identified air stagnation zones at various other locations in the OR depending on the room design and medical appliance arrangement under both LAF and TMA systems [58–60].

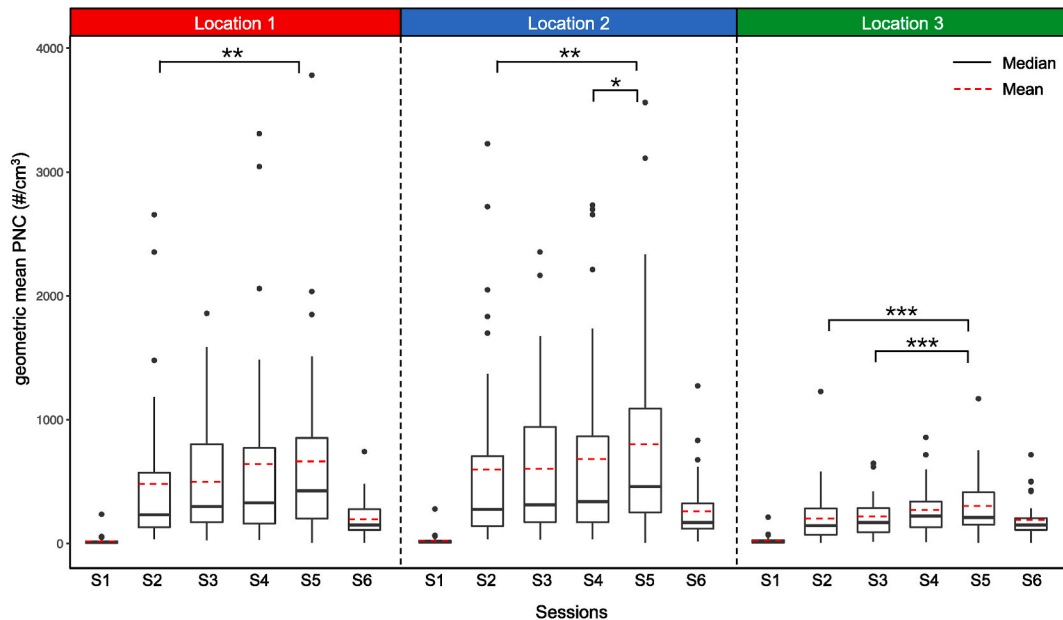


Fig. 3. Comparisons of geometric mean PNC between test sessions at three sampling locations. Boxplots show the median (solid line) and IQR (25th and 75th) of geometric mean PNC for all 40 patients. Red dashed line represents the mean. Paired Wilcoxon signed-rank test was conducted between two sessions, using two-sided alpha level of 0.05 for statistical significance (* < 0.05; ** < 0.01; *** < 0.001). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

By comparing the PNCs between locations, we noted that the PNC levels at Location 2 (physician) were slightly higher compared with Location 1 (reference) (Fig. S2), though Location 2 was closer to the central ventilation inlets. In practical settings, physicians perform operating procedures close to the surgical table, underneath the surgical lamp and monitors suspended from the ceiling. In addition, physicians are also surrounded by HCWs supporting the surgery. Indeed, various studies have identified disturbed air distribution due to surgical lamp and medical personnel both quantitatively and qualitatively using bacteria carrying particle counts [61, 62] and CFD visualization techniques [57,63]. These obstacles have been shown to deteriorate the function of ventilation due to impeded air distribution [11]. Given the stationary and essential nature of surgical appliance and HCWs, mobile LAF devices might be utilized to remove aerosol particles at the operating microenvironment of the physicians [64].

Location 3 (medical assistant location) had significantly lower PNCs compared to the other two locations across all test sessions (Fig. S2). From sessions S2 to S5, the median PNCs at Location 3 were significantly lower compared to Location 1 (Table S4). Besides ventilation dilution effect, the decreased PNC levels observed at Location 3 may also be attributable to the proximity effects, as Location 3 was further away from the emission source which further contributed to diluted particle levels [65].

3.3. Particle removal at three sampling locations

Fig. 4 shows the particle decay rate at Locations 1, 2, and 3, respectively, with 23, 24, and 9 valid decay sessions (S6) included for analysis (See exclusion criteria in 2.5 Statistical Analysis). The mean decay rates at Locations 1, 2, and 3 were $50 \pm 20 \text{ h}^{-1}$, $46 \pm 22 \text{ h}^{-1}$, and $33 \pm 21 \text{ h}^{-1}$, respectively (Table S5). Based on the study setup, Locations 1 and 2 were within the same airflow trajectory as they were placed on the same IV pole directly beneath the ceiling ventilation inlets. Thus, similar decay rates were observed at Locations 1 (50 h^{-1}) and 2 (46 h^{-1}). Nonetheless, the decay rate observed at Location 2 (physician) was marginally lower than that at Location 1, suggesting deteriorated ventilation effect, as obstacles such as surgical lamp and monitors may contribute to impeded airflow and affect particle removal [33].

In comparison, Location 3 was placed by the waist side of the surgical table, further away from the other two locations and subject to a distinct airflow pattern. Location 3 presented more than a 30 % decrease in mean decay rate compared to the decay rates at Locations 1 and 2 (Table S5). However, it should be noted that Location 3 had lower PNC levels throughout the test compared to the other two locations (Table S4), which might affect decay rate calculation. The mean decay rates obtained at all three sampling locations were considerably higher than the AER technical standards of the OR ventilation (20 h^{-1}) [44], as well as the measured AERs ($\sim 20 \text{ h}^{-1}$) in the ORs from previous studies [66,67]. These high decay rates obtained in this study suggest that the TMA ventilation system in the ORs is highly effective.

3.4. Expected particle levels for selected surgeries

To provide further insights into the effectiveness of OR ventilation system on particle removal, we reviewed and compiled literature that quantified particle generations using PNC levels from different types of surgeries. Studies showing small or no meaningful increases in PNCs, such as myringotomy and rhinologic surgeries [68–70], were excluded from analysis.

According to the reviewed studies, the peak PNCs for most surgeries reached above 10^4 particles/cm³, with abdominoplasty, nephrectomy, breast reduction, hip replacement, and otorhinolaryngology surgery exceeding 10^5 particles/cm³ at the physician and medical assistant locations, respectively [30]. Based on the assumption that the ORs in the reviewed articles had a similar TMA

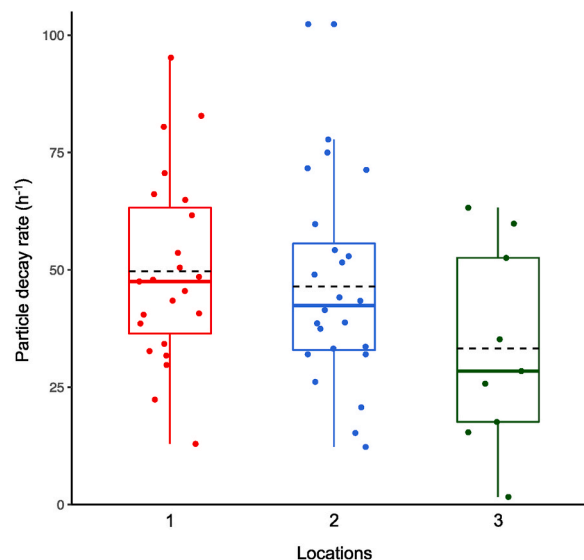


Fig. 4. Particle decay rate at three sampling locations. All valid decay sessions were included for decay rate calculation. Each box provides the median decay rate in colored solid lines. The 25th and 75th percentile (IQR) are represented by the lower and upper boundary of each box. Black dashed line shows the average decay rate. Each dot represents individual decay rate measured for each patient.

ventilation installed, we utilized the particle decay rates obtained from our setup and estimated the anticipated PNC for each surgery after a brief duration of 1 min and 10 min. As shown in Table 1, none of the PNCs from the selected surgeries returned to the baseline level of ~ 10 particles/cm³ after 1 min of particle decay at each sampling location (Table S4). Following a particle decay of 10 min, only three surgeries exhibited PNCs that reverted back to the baseline level, including abdominoplasty at the physician location, otologic drilling outside surgical table, and endoscopic sinonasal drilling at the physician location [71]. Therefore, even with high decay rates, most reviewed surgeries required more than 10 min to adequately remove particles generated by the respective surgical procedures. A recent study conducted by Massarotti et al. [49] incorporated both CFD models on identifying OR air velocity and UFP measurements in an experimental OR with an AER of 24 h⁻¹ reported a peak PNC of 4×10^5 particles/cm³ and estimated a decay time of 19 min for UFPs to be evacuated. Therefore, HCWs likely face elevated particle exposure risks for extended periods in surgeries that generate large number of particles.

Given the distinct operating durations and surgical activities involved for different surgeries, the OR environment for each surgery may be varied. As a result, particle exposures in the OR for each unique surgery need to be evaluated separately [12,37]. It is worth noting that the surgeries reviewed do not include respiratory aerosol generating procedures due to a lack of available studies. Therefore, additional research is needed to provide a better understanding of the ventilation mitigation on respiratory particles during surgeries involving highly infectious respiratory diseases.

4. Study limitations

This study has several limitations. First, since all tests were conducted in real operating condition, we were limited to measuring particles for a duration of 1 min for each session to avoid surgical procedure disruption and possible patient harm. Thus, we were unable to allow the PNCs to fully decay and return to the baseline in S6. Nonetheless, the initial phase of particle decay was available, which enabled us to estimate the decay rate at three sampling locations. Second, it should be noted that the installation standards for TMA systems may vary across different countries and hospitals. Consequently, the ventilation air inlets and exhaust outlets may be of differing sizes and installed in distinct locations within the OR [31]. Thus, results obtained from this study should be generalized to other ORs with caution. Finally, nebulizer-generated particles were used as the particle emission source in this study in conjunction with patient respiratory activities (i.e., deep breathing and coughing). Given both ethical considerations and data collection requirements, we choose to employ a nebulizer that could generate a continuous stream of particles to challenge the ventilation performance. To ensure practicality, we maintained the peak particle generation at $< 10^5$ particles/cm³ to prevent the overestimation of particle generation while ensuring proper functioning of the CPCs. As different surgeries are performed differently at varying locations around the surgical table, our findings can be more reliably generalized to surgical operations that encompass general endotracheal anesthesia.

5. Conclusions

This study aimed to test the effectiveness of OR ventilation in mitigating and removing aerosol particles during general endotracheal anesthesia at three representative working locations around the surgical table. The results showed that the PNC levels were significantly higher during intubation (S5) compared to other sessions, possibly due to the disruptive effect of operating activities. Significantly lower PNC was observed at the medical assistant location (Location 3), potentially attributable to particle dilution as well as obstructed particle transport due to obstacles such as surgical lamp and HCWs. The particle decay rates at Location 1 and Location 2 were comparable (50 h⁻¹ and 46 h⁻¹, respectively). However, the decay rate at Location 3 (33 h⁻¹) was 30 % lower compared to those at the other two locations. Nonetheless, the particle decay rates at all three locations were considerably higher than the OR AER standard (20 h⁻¹), suggesting highly efficient ventilation function. The TMA system used in this study is not expected to reduce the peak PNC levels of most reviewed surgeries back to the baseline within 10 min of functioning. Thus, HCWs should be cautious about prolonged exposure risks during surgeries that generate a large number of particles. This study provides numerical evaluation of OR ventilation system on mitigating fine and ultrafine particles in real-world OR operational conditions, which has the potential of facilitating CFD model development in the OR environment. Given the prolonged particle evacuation duration estimated for surgeries that generate large number of particles, urgent needs exist on establishing OR regulation on fine and ultrafine particles. To prevent the formation of air recirculating and stagnating zones during particular surgical activities such as intubation in this study, future research may focus on the optimization of surgical appliance arrangement and the usage of mobile LAF devices to improve the effectiveness of ventilation.

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Declaration of generative AI in scientific writing

During the preparation of this work, the authors used ChatGPT in order to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRedit authorship contribution statement

Muchuan Niu: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. **Haoxuan**

Chen: Data curation, Methodology. **Jonathan Liu:** Data curation, Formal analysis. **Chi-hong Tseng:** Formal analysis. **John Shin:** Conceptualization, Project administration, Resources. **Nir Hoftman:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision. **Yifang Zhu:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests of personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.job.2024.108596>.

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